Computer Programming For Power Systems Analysts.

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INTRODUCTION

"Computer programming for power systems analysts" treats the subject of the electrical power systems distribution and analysis from a problem solving point of view.

Chapter 1 offers an introduction to computer programming using two languages. The two languages are: Basic and C++. The main statements in each language that are required to build the programs that will solve the power systems problems were given, also, in this chapter.

Chapter 2 presents an overview of the electrical power system including the equipment used and is divided into generation & transmission, subtransmission & distribution and utilization. The emphasis was put on the subtransmission and distribution levels of the power distribution system. The other topics that were included in this chapter can fall under base values calculations and basic operations to be performed on the mathematical models representing the power systems components and problems. The chapter is divided into two sections, the first covering the topics from the power angle and the second from the programming view point which gives a few complete example programs to solve certain problems and achieve specific results.

Chapter 3 is divided into two sections, also. One for the coverage of the faults in power systems topic from the power side as well as the other from the programming angle in which a few examples were given to calculate the fault currents and the voltage sensitivity of the healthy (unfaulty) buses for certain

fault types.
Chapter 4, following the same format as the previous chapter but covering the load flow topics was presented in two sections, also. One section covering the methods of solving these studies, the modelling of typical systems and finally the equations used in the calculations were given. The second section gave the example programs for the specific systems.
Chapter 5 covered the transients in power systems, the modelling of the different equipment, the methods used to analyze for transients, their causes. The first section covered the topics from the power angle and the second listed a few problems that calculates the overvoltages imposed on the systems under certain operating or design conditions.
Chapter 6 covered the topic of reliability in industrial plants and utility distribution. The same format used in chapter 2 was used also here. The first section covered the modelling and the methods used to quantify the reliability of the system. The second section presented a couple of programs that may assist in analyzing the reliability of the different industrial designs as well as the utility feeders.
Chapter 7 covered, using the usual format, the stability topic including the types of stability studies, the types of disturbances that may cause the system to go out of synchronizm, the equations used, the type of stability problems.
Chapter 8 covered the topic of "electrical power distribution management information systems" which included the major equipment of a power system with the necessary data for each equipment (category) type to build such a data base.
Chapter 9 covered the engineering economics analysis methods and tools that are required in order to enable the power system analyst to evaluate economically the operation of the different equipment and systems that build a power distribution plant.

The self testing questions section (after chapter 9) gave a few questions (75 in all) which were divided based on the 9 chapters in this book. This section may assist the reader in developing a self evaluation process in which the outcome would show how much he or she had gained from this book.
Appendix A gave a sample input and output data to the example programs given in the chapters 2 to 9 (the exception is chapter 8).
Appendix B gave a brief introduction to Windows programming using ObjectWindows.

CHAPTER 1
INTRODUCTION TO COMPUTER PROGRAMMING

The main three (3) parts of any program are: the user input data, the operations to be performed on the data entered and the output of the results of the operations to the screen or to a file on the floppy or hard disk. Programming languages, whether procedural or object oriented, will have statements and syntax to use and follow to achieve an operable program and to obtain the expected results from the written programs. The major elements that build a program are, function of the language: the data types, operators, control statements, looping (iterating) statements, input/output statements, subroutines/functions/chaining and the language specifics portions (e.g. for C++: header files included in the program file, the class/structure/enum). The elements used in this book to write the programs that solve the power systems problems and perform the power systems studies/analysis will be covered in sections 1 and 2, in a general sense. Section 1 will cover those statements pertinent to basic language and section 2 those to C++.

I. BASIC:

1. Prompts and user data input:

•• INPUT statement: allows input from the keyboard while the program is running.

eg.: 1) INPUT "The reactance or resistance in the first leg 1-n or 2-3"; X
  2) INPUT "filename to save this file under", filename$

2. Output data to screen or file:

•• PRINT statement: outputs data to the screen.

eg.: 1) PRINT "Fault current in p.u. = "; 3*i
2) PRINT "Voltage on bus #2: zero, +ve & -ve sequence and phases A,B&C respectively = "; vs210, vs211, vs212, vs2af, vs2bf, vs2cf.

•• PRINT # statement: writes data to sequential file.

eg.: 1)PRINT #1, "voltage on bus 1 at time of fault on bus 5 in p.u. = ", vf * (1- Y15/X111)
2)PRINT #1, "voltage in p.u. on bus 1, phases A,B&C, respectively = "vsaf, vsbf, vscf

3.Control of program flow:

•• IF...THEN (single line): allows conditional execution based on the evaluation of the expression following IF.

eg.:1)IF nb=1 THEN CALL ZZ (zng, tng, tc)
2)IF mxs=3 THEN CHAIN "gauss 8x8"

•• IF...THEN, ELSE, END IF: same as above

eg.:1)IF X02> 0 THEN
CALL a (X11, X12, X21, X22, X02, X23)
ELSE
X31 = X21
X32 = X22
X33 = XX23+X22
X13 = X12
X23 = X22
END IF

4. Looping (iteration) of specific program instructions.

•• For, NEXT statement: repeats a group of instructions for a number of time
eg.: 1) FOR i = 1 TO nit
Instructions
NEXT i

5. Subroutines and programs chaining:
•• COMMON SHARED: define global variables for sharing between modules (subroutines and functions) or for chaining to another program.
eg.: 1) COMMON SHARED rb, zng, tng, tc
•• SUB, END SUB: marks the beginning and end of a program.
eg.: 1) SUB az (b1, b2, b3)
Statements and instructions
END SUB
2) SUB a
Statements and instructions
END SUB
•• DECLARE: declares references to procedures (functions or subroutines) and invokes argument-type checking.
eg.: 1) DECLARE SUB az (b1, b2, b3)
2) DECLARE SUB a ( )
•• CALL statement: transfers control to a SUB.
eg.: 1) IF nb=1 THEN CALL az (zng, tng, tc)
2) IF nb=2 THEN CALL a
•• CHAIN statement: transfers control from the current to another program.
eg.: 1) IF nfs = 2 AND nbs = 6 CHAIN “motstbb3"

6.Operators: they can be classified into relational/logical and mathematical. The relational are: equal (=), not equal (<>), less than (<), less than or equal (<=), greater than (>) and greater than or equal to (>=). The logical are: AND, OR, NOT, EQV, XOR and IMP. The mathematical are add (+), subtract (-) , to the power (^), divide (/) and multiply (*). The trigonometric functions are the sine of an angle (in radians) (SIN), cosine (COS), tangent (TAN), the arctangent (the angle in rad.) of the numeric expression (ATN).
eg.: 1) vs10 = y180 * (i fault/3)
2) vscr = vs10+(-.05)*(vs1i)+(-.5)*(vs12)
3) Vsbf = ((vsbr)^2+(vsbi)^2)^.5
4) an12 = ATN (x12/r12)
5) b12 = y12*SIN (-an12)
6) g12 = y12*COS (-an12)

7. Saving data files (overwrite or append):
•• OPEN filename$ FOR APPEND AS #1: enables the input to a file, appending it with the new output data of a program. The number of the file is 1. To write data data to the file use PRINT #1, “...”.
•• OPEN filename$ FOR OUTPUT AS #1: open a new file or overwrite an existing file with the name filename $ (this is a string variable that can get any name with an INPUT statement - a string name with the usual limitations).
•• CLOSE statement: concludes input to a file.

eg.: 1) CLOSE #1

8. Other useful statements:
•• Control of program flow:
SELECT CASE statement: executes one of several statement blocks depending on the value of an expression.
eg.: SELECT CASE a
CASE “1"
instructions
CASE “2"
instructions
CASE ELSE
instructions
END SELECT
•• Looping (iterative) statements:
1)DO UNTIL, LOOP, repeats a block of statements until a condition becomes true. Testing can be at beginning or end of loop.
eg.: 1) DO UNTIL a condition
instructions & statements
Loop
2) DO WHILE, LOOP repeats a block of statements while a condition is true.
eg.: 1) Test at beginning of loop
DO WHILE a condition
Statements
Loop
eg.: 2) Test at end of loop
DO
statements
Loop WHILE a condition
•• Miscellaneous statements:
1)DATA statements: stores the numeric and string constants used by a program is READ statement.
eg.: 1) DATA "   "
.   2) DATA " I.M. 3600 RPM "
2)READ statement: reads values from a DATA statement and assigns the values to variables.
eg.: 1) READ temp$
3) RESTORE statement: allows DATA statements to be reread from a specified line.
eg.: 1) RESTORE cardscreen 13
.   2) RESTORE cardscreen 13a
4) Locate statement: moves the cursor to the specified position.
eg.: 1) LOCATE row, 1
5) INKEY$ function: reads a character from the keyboard.
eg.: 1) uchoice$ = INKEY$
6) LCASE$ function: returns a string expression with all letters in lower case.
eg.: 1) LCASE$ (uchoice $)
7) CHR$ function: returns a one character string whose ASCII code is the argument.

eg.: 1) CAR$ = CHR$ (13)
Note: 13, decimal base, is a carriage return.
8)ON ERROR statement (an error trapping/event handling one): enables error handling and specifies the first line of the error handling routine (label).
eg.: 1) ON ERROR handler
handler:
BEEP
Note: BEEP: sounds the speaker
9)RESUME (error handling) statement: continues program execution after an error- trapping routine has been invoked. Causes the program to branch back to the exact statement that caused the error.
10)RESUME NEXT (error handling) statement: causes the program to branch back to the statement following the one that caused the error.

II. C++:
The tools offered by this language to control the computer and the connected resources are most powerful. This language is known as the high level assembly one. Broadly, the files in C++ can be classified into header files, methods program and implementation files. The methods file will refine the functions declared in the header file and the implementation (having the main function) file will use the header file with .H extension and the methods file with .CPP extension to get the required performance and results (output). For a short program the compiled and linked file from the source code will have the following parts: list of header parts eg. # include <iostream.h>, the list of global variables and their data type eg. float v[33], d[33], z45; the base class eg. class load_flow {; the definition of the functions declared in the class with the scope resolution operator between the class name and function name plus the data type expected from the function ahead of the class name eg. void load_flow::input ( ) { and finally the main function, which is the entry point to the program. In order to have a full grasp on this language the following topics have to be understood: predefined and creating classes, pointers and references, overloading functions and operators creating objectsat run time, arguments and return values and may be containers and templates. A lot of well written books that cover C++ in general for the sake of the software itself rather thanspecifically its application to the electrical power field are available. This is not the objective of this book. The main objective of this book is to show how are the problems and calculations in the power systems field can be solved using certain elements of C++ object oriented programming language or quick basic procedural language.
1. Prompts and user data input.
•• cin >> (header file to be included in source code <iostream.h>)
ie.:# include <iostream.h>): allows input from the keyboard while the program is running.
eg.: cin >> V[2] [0];
Cin >> P6;

2. Output data to screen or file:
•• cout << (header file: <iostream.h>): outputs data to the screen.
eg.: 1) cout << “voltage at bus 2 in p.u.:”;
2) cout << “active power from bus 1 towards 2 in p.u. = ”<<pfa12<< endl;
•• ofstream (include header file: <fstream.h>): Saves data to data file.
eg.: 1) ofstream fout (filename);
fout <<”voltage on bus 2 = “<<v[2] [itn]<< endl;
fout. close ( );

3. Control of program flow:

•• if: allows conditional execution based on the evaluation of the expression following the if.

eg.: 1) if (nf = = 3){
instructions
}

2) if (bn = = 3 && nf = = 2){
instructions
}

•• switch, case: allows conditional execution based on the evaluation of the expression after switch.

eg.: 1) switch (response) {
case 'a':
instructions
case 'b':
instructions

4. Looping (iteration) of specific program instructions:

•• while: repeats a block of statements while a condition is true.

eg.: 1) while (quit = = 0){
instructions
}

•• for: repeats a group of instructions for a number of times.

eg.: 1) for (int i = 0; i<itn+1; i=i+1){
instructions
}

5.Operators & trigonometric functions: operators in C++ are classified into: arithmetical, logical, bit-level manipulations, structure and union component access and pointer operations (referencing and dereferencing). The unary operators are: address (&), indirection (*), unary plus (+), unary minus (-), logical negation (!), preincrement or postincrement (++), predecrement or postdecrement (--). Logical operators are: and (&&), or (| |). The binary operators are: equal to (= =), multiply (*), divide (/), assignment (=), less than (<), greater than (>), less than or equal to (<=), greater than or equal to (>=), not equal to (!=). The header file to be included in the source code is the <math.h> to be able to calculate the following functions: sqrt (x): calculates the positive square root of x, pow 10(p): calculates 10 to the power of integer p, pow (x,y): calculates x-a double type - to the power of y- double type, sin (x): calculates the sine of the angle x in rad., tan (x): calculates the tangent of the angle x in rad., cos (x): calculates the cosine of the angle x in rad., atan (x): calculates the arc tan of x and gives it in rad.

eg.: 1) z121 = ((r12) * (r12) + (x12) * (x12));
2) z12 = sqrt (z121);
3) an12 = atan (x12/r12);
4) g12 = y12 * cos (-an12);
5) b12 = y12 * sin (-an12);

6. Language specifics:
   • classes: a class is a new abstract data type that is created to solve a particular type of problem,
   eg. class load_flow
   {

public:
void input ( );
void solution ( );
void two_feeder (int itn=0);
void power_flow (int itn=0);
};
Once a class is created, anyone can use it without knowing the specifics of how it works, or even how classes are built. A declaration tells the compiler where and how the function is and looks like. The definition tells the computer where to make the data or the function. The declaration (of data or functions) can appear in many different places. Only one definition should exist for the function or data piece.
eg.: For declaration
eg.: 1) void input (int nf=0);
2) void two_feeder (int itn=0, int nf=0)
eg.: For functions
eg.: 1) void load_flow :: input (int nf)
{statements & instructions
}
2) void load_flow :: two_feeder (int itn, int nf)
{statements & instructions
}
Note:cin, cout and the likes are objects and >> is an example of an operator. Type specifiers may be any of the following long, short, signed and unsigned for the data types char, int, float and double. The class is constructed, the functions are defined and in the entry point of the program (the main function) the instructions to work on the classes and functions are given, now the program is considered operative.
eg.: 1) class load_flow {
void input ( );
void two_feeder (int itn=0);
};
void load_flow :: input ( ) {
instructions and statements
}
void load flow :: two_feeder (int itn) {
instructions & statements
}
void main ( ) {
load_flow problem
instructions and statements
problem.input ( ) ;
problem.two_feeder (itn1);
other instructions & statements
}
There are, in total, three access specifiers (which allow a function to access data objects and

other functions from the same or the derived classes): public, protected & private. If a function has to access data or function of another class, the data and functions have to be public (have public access specifier). The member functions can access all private data members and functions of their own class. They can also access all protected data members and functions of any class from which they derive. Scoping rules tell where a variable is valid, where it is created and where it gets destroyed or goes out of scope. When variables are created their lifetime, storage allocations and the way to be treated by the compiler have to be specified. Variables are classified into global, local and register. The first are defined outside the function body and are available to all parts of the program even in other files. The second type of variables are local to the function where they are created. The third is a type of local variables. Static keyword can be used with variable that is to be initialized once at the beginning of the program execution and the data is to retain its value between function calls. Extern keyword tells the compiler that a pieceof data or a function exists, even if the compiler has not yet seen it. Linkage describes the storage created in memory to represent an identifier as it is seen by the linker. An identifier is represented by storage in memory that holds a variable or compiled function body. There are two (2) types of linkage internal and external. Typdef keyword indicates that a new data type is defined. The identifier can be modified through the use of modifiers eg. const and volatile.

•• Pointers and References: The pointer is another data. It has its own rules and can be manipulated with all the operators available for the ordinary data types. The distinction between the definition of an ordinary variable and the definition of a pointer (symbol *) is *. The * means at this address, what is in this memory location (analogy to mail box). References allow the programmer to control the way arguments are passed to functions. The symbol & (address of operator).

eg.: void funct (constant data type*);

funct (&A);

A reference has the property of a pointer and a variable, like a pointer it contains an address and like a variable as it does not have to be dereferenced.

•• Constructors: initialization of a variable combines the definition of the variable with its initial assignment. Classes have a special member rfunction called a constructor. It is a class method with with the same name as the class itself. The different types of constructors are: default, copy and virtual. The default constructor is provided by the compiler if no constructor is provided in the class. The copy constructor is either the default, member wise (known also as shallow) or deep. The default constructor is provided by the compiler and is called everytime a copy of an object is made.

•• Overloading operators and functions:

Overload means giving the operator or function a new additional meaning. To overload an operator, a definition of a function for the compiler to call when the operator is used (with the appropriate data types) has to be available. Multiple functions can exist to overload a single operator. Each function must take different arguments. The function name has to be always the keyword "operator" followed by the operator itself, then the argument list plus the function body. Functions overloading means functions with different argument lists but with the same name can be created.

Notes: The keyword "friend" is used to allow objects outside the class access private elements functions of the class. A friend has the same access privileges as a member function, but it is not associated with an object of the host class. Keyword "this" means the starting address of the object for which this function was called, it is the same as the address of the first variable in the class.

Contents

CHAPTER 2
OVERVIEW OF ELECTRICAL POWER SYSTEMS AND BASIC VALUES CALCULATIONS

A.C. Electrical power systems will have any or all of the following components: generators (complete with their prime movers and control devices), isolated phase bus, instrument transformers, switchgear assemblies, transmission lines, transmission towers, circuit breakers, fuses, relays, meters, transformers, disconnect switches, load break switches, lightning arresters, poles, overhead conductors, underground cables, reclosers, sectionalizes, padmounted switchgear, cable terminations, splices, connectors, supports, synchronous/induction motors and other loads. Broadly any of the above elements can fall in one or more of the following categories: generation and transmission, distribution (including subtransmission) and utilization. The voltage in general of the electrical power equipment can be low (up to 1KV), medium (up to 72 KV) or high (over 72KV & up to 745) voltage.

I. Power Section:

I-1 Generation and transmission:

I-1-1 Synchronous generators: the flux of the machine is produced by a direct current. The pole structure of the synchronous machine is the inner part of the machine which rotates. The armature is the outer part and is stationary. The types of rotors in synchronous machines are the salient (for lower speeds) hydro driven generators and the cylindrical (non-salient) steam turbines driven which are used in higher speeds machines. The rotors may have punches with a winding similar to a squirrel cage which acts as dampers to oscillations in generators and to start the machine when operating as a motor. This winding is called damper or amourtisers. The characteristics of synchronous generators are: the no load and air gap (unsaturated), short circuit (Potier), load, external, regulation, short circuit ratio/direct axis synchronous reactance. The synchronous generator is represented by a field winding with resistance and inductance (R_f & L_f), the d-axis (direct), the q-axis (quadrature), the armature phase A resistance and inductance (R_a, L_a), the armature phases B and C resistances and inductances (R_b, R_c, L_b & L_c), the mutual inductances between phases A & B, phases B & C, phases C & A and the mutual inductances between the field and phases A, B & C. The single-axis model is used in steady state analysis and the two-axis model for transients studies (where the q-axis and d-axis are taken into consideration).

Terminal voltage (v_a) = $- R\, i_a - (L_s + M_s)\, (di_a/dt) + e_a'$

No load voltage (e_a') = $(2)^{.5}\, |E_i| \cos(\omega\, t + \delta)$

$|E_i| = \omega\; M\, f\, If\, / \,(2)^{.5}$; where L_s is the self inductance of the concentrated coil A, M_s is the mutual inductance between each adjacent pair of concentrated coils, R_a is the resistance of coil A, $|E_i|$ is the rms value of induced emf in coil A.

Terminal field voltage (v_f) = $R_f\, i_f + d\, \lambda_f / dt$

$I_f = (2)^{.5}\, |E_i| / \omega\; M_f$, $\lambda_f = L_f\, I_f - [3M_f / (2)^{.5}]\, |I_a| \sin \theta\; a$

$(3)^{.5}/2\; M_f$ is the mutual inductance between the field winding (circuit) and the fictitious circuit

coincident with the d-axis (the flux linkages of the 3 phase currents with the field winding).
The synchronous impedance (Z_s) = R + jX_s= R + j (L_s+M_s)

Apparent power delivered to the system from the generator = S = P + jQ = V_t I_a (cos θ + j sin θ)

P = (|V_t| |E_i| /X_s) sin δ . Q= (V_t / X_s) (|E_i| cos δ - |V_t|)

The loading capability of round rotor generators will have five possible operating modes, one parameter of the generating unit is kept constant at any time. The loading capability diagram (operation chart) will have: the constant excitation circle, the constant armature current circle, the constant power straight line, the constant reactive power straight line, the constant power factor radial line. For the equivalent circuit of a generator (alternator) under different conditions, click here.

The two axis model is presented by a salient (non round rotor) pole machine. In such machines the air gap is much narrower along the direct axis than along the quadrature axis. Such a machine can be presented by the following elements:

-For the stator:self inductance of coils a, b & c,the mutual inductance between the pair of coils.
-For the rotor: self inductance of the field and dampers (in the D and Q windings), the mutual inductance between the pair of coils (field, D and Q windings).
-For the stator/rotor: the mutual inductance between the armature coils and field, D and Q damper windings on the rotor. The three stator currents ia, ib and ic can be transformed into 3 equivalent currents: id (direct-axis),iq (quadrature axis),io (zero sequence) - using Park's transformation.

$$P = \sqrt{2/3} \begin{bmatrix} \cos\theta_d & \cos\theta_d\text{-}120 & \cos\theta_d\text{-}240 \\ \sin\theta_d & \sin\theta_d\text{-}120 & \sin\theta_d\text{-}240 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \qquad \begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} = P \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

The same can apply to the voltage and flux linkage. The zero sequence (armature) winding is considered fixed with no mutual inductance (coupling) with any other coils.

For salient pole machines: v_a = -R i_a - d λ a / dt, v_b = -R i_b - d λ b / dt, v_c = R i_c - d λ c / dt.

v_d = -R i_d - d λ d/dt - ω λq, v_q = -R i_q - d λ q / dt + ω λ d

v_f' = -R_f i_f + d λ f / dt; where ω λ q and ω λ d are rotational emfs (speed voltages internal to the machine due to the rotation of the rotor). It is worthwhile mentioning here that any electric machine is governed by any or all of the following laws: Kirchoff's voltage, Faraday's induction, Ampere's circuital, Biot Savart's force on a conductor and the force on a conductor because of a close by current carrying conductor. In short circuits studies, only direct axis quantities are involved (in 3 phase short circuits), on reactive networks. When the machine has an active power loading (before the disturbance), quadrature-axis quantities are also involved as in q-axis current i_q exists and constant flux linkages must be maintained with the q-axis rotor circuits during these changes. The direct axis transient reactance is the ratio of the fundamental component of reactive armature voltage (due to fundamental d-axis ac component of the armature current) to this component of current under suddenly applied load conditions (at rated frequency). The current value is the extrapolation of the ac current envelope (neglecting the high decrement currents during the first few cycles). The same applies for transient q-axis reactance. The direct axis subtransient reactance is the ratio of the fundamental component of reactive armature voltage due to the initial value of the fundamental d-axis ac component of armature current to this component of current under suddenly applied load conditions (at rated frequency). The direct axis short circuit transient time constant, T_d' determines the decay of the transient envelope. It is equal to the time required, for the envelope, to the point where the difference between it and the steady state envelope is .368 p.u. of the initial difference between the envelopes. The direct axis short circuit sub-transient time constant, T_d'' determines the decay of the subtransient envelope, it equals the time required for the envelope to decay to the point where the difference between it and the transient envelope is .368 of the initial difference. The armature time constant, T_a, determines the decay of the dc component, it is equal to the time required for the dc component to decay to .368 of its initial value.

L'_d (d-axis transient inductance) = $\Delta \lambda d / \Delta i_d = L_d - (K M_f)^2 / L_f$, $X_d' = \omega L_d'$; where Ld is the direct axis inductance, $K= (3)^{.5}/2$, L_f is the field coil self inductance, M_f is the maximum value of the mutual inductance between the field coil and each of the armature (stator) coils (or the equivalent winding).

L_d'' (d-axis subtransient inductance) = $\Delta \lambda d / \Delta i_d$

$= L_d - K^2 [M_f^2 L_D + M_D^2 L_f - 2 M_f M_D Mr/L_f L_D - Mr^2]$

$X_d''= \omega Ld''$; where L_D is the self inductance of the d-axis damper (D-winding) coil, M_D is the mutual inductance between the rotor D-damper winding and the equivalent d-axis armature winding and M_r is the mutual inductance between the D-damper winding and the field winding. The d-axis transient reactance can be given as the armature leakage reactance plus a modified field leakage reactance term, $X_d'= X_a + [X_f (X_d)/X_d+X_f]$; where X_a is the armature reactance, X_f is the reactance of the field winding and X_d is the d-axis magnetizing reactance for the fundamental frequency steady state armature currents. Transient time constants are: the open circuit transient time constant (T_{do}'), the S.C. time constant (T_d') and short circuit adjusted for external reactance (T_{de}').

$T_{do}' = (X_f + X_d)/2 \pi f r_f$; where r_f is the field winding resistance.

$T_d' = [X_f + X_d) (X_d')/X_s (2 \pi f r_f) = T_{do}' (X_d'/X_s)$

$T_{de}' = T_{do}' (X_d' +X_e)/(X_s+X_e) = T_d' (X_s) (X_d' + X_e) /[(X_d') (X_d+X_e)]$

Similar equations can be used to calculate the time constants for subtransient condition.

The amplitude of the ac component of each phase current can be expressed accordingly.

$I(t) = |E_i|/X_d + |E_i|(e^{-t/T_d'})(1/X_d' - 1/X_d) + (|E_i| e^{-t/T_d'}) (1/X_d'' - 1/X_d')$.

$|I| = |E_i|/X_d$, $|I'| = |E_i|/X_d'$, $|I''| =|E_i|/X_d''$.

The ratings and other factors that are important in power system analysis are the rated voltage, rated MVA, the H constant MJ/MVA, speed, active/reactive power, no load/air gap/locked rotor characteristics, damping/excitation/governor/regulator/steam systems (whatever applicable) limits/properties and reliability data (if available).

I-1-2 Transmission lines: this topic will be divided into two main sections: mechanical and electrical aspects.

The mechanical aspects include the following: regulation, conductors materials and stranding, sag and tension including ice and wind effects, grounding (earthling) and vibration/damping. *The electrical aspects* include: the conductor resistance/inductance/capacitance, disruptive critical voltage, visual critical voltage, corona discharge, corona power loss and insulators. The designs should comply with the local authorities regulations and standards. Overhead lines are cheaper than underground cables, easier to apply higher voltage, accessible easily for extension and repairs. The disadvantages of overhead lines are exposure (to, for example, lightning and ice) and possible interference with communication/data lines. The conductors for overhead system must comply with the applicable standards when it comes to elongation, breaking load, elasticity, safety factors, clearances, supports strength, treatment, accessibility of line conductors, corrosion of metal parts (above and below ground), grounding (earthling) requirements including overhead ground conductors, grounding of supports, neutral wires, hardware and equipment installed in overhead transmission systems. The conductors are built from copper or aluminum, solid or stranded. The axial length of a spiral or a wire in a layer is called a lay and is expressed in multiples of the mean diameter of the layer containing the wire, the higher the value the higher the effect of the lay in decreasing the resistance of the wire. For a stranded conductor, the total number of strands = 3n (n+1) + 1; where n is the number of layers and the overall diameter of the conductor = (2n+1) d; where d is the diameter of the strand. Other materials used in conductor construction are alumweld, copperweld, steel. The resistivity of annealed Cu, Hard-drawn Cu (97.66%), hard drawn Cu (96.66%), aluminum (AL 1350), Al Alloy (6101) is (in $\mu\ \Omega$): .017241, .017654, .017837, .028264 and .03253, respectively. The conductivity of copperweld is 30 or 40% of that of a copper conductor with equal diameter. For a transmission line supported at 2 points, the equation of the line is: y =H/W [cosh (WX/H)-1]; cosh WX/H=1 + $(W^2X^2/H^2)(1/2!) + (W^4X^4/H^4)(1/4!)$ + ... =
½ [e^z; + e^{-z}], Z=WX/H; where W is the weight of the line per unit length X is the distance from the origin (chosen at the lowest point in the span) in the horizontal direction, H is the horizontal tension at origin. The tension at point P = T = H cosh WX/H. The sag d is the value of y at one or the other support.
d = (H/W) [cosh (Wl/H)-1]. The length of the line at half span S = H/W sinh Wl/H, sinh (WX/H) = WX/H + $W^3\ X^3\ /H^3$ (3!) +...
The wind and ice will have an effect on the mechanical loading of the conductor. The total force on 1 ft of conductor W = $[(W+W_i)^2 + W^2_w]$, W_i = 1.25 R (D+R) LB; where W_i is the weight of ice/ft assuming 57 lb/ft^3, D is diameter of conductor in inches and R is radial thickness of ice. Ww = F(D+2R)/12 where Ww is maximum wind pressure /ft. run, F is the pressure exerted in LB/ft² (for eg. 8).
The sag and tension of conductors are function of temperature and elasticity. The maximum sag should not reduce the clearance of the conductor from ground or other circuits below the values indicated in the standards and required by the regulatory bodies. Stringing charts are used to indicate the appropriate sag values at time of installation, taking into consideration the temperature at time of installation and the maximum allowable sag including loading (of ice and winds). The stringing chart will also have a curve between the temperature and the tension (in LB for example). The following equations are used to calculate the stress f_2 and the corresponding sag d_2:
$f2^2\ [f_2-F] = G$; $d_2 = W\ l^2/2T_2 = W_2\ l^2/2\ f_2A$

$F = f_1 - W^2 l^2E/6 T_1^2 - (\theta_2 - \theta_1)(\alpha E)$ and $G = W_2^2 l^2E/6A^2$; where A is the cross section of the conductor, α is the coefficient of linear expansion, E is the Young's modulus (of elasticity) of the conductor, w1/f1/s1/d1/ θ_1 are, respectively, the load per unit length/ stress (tension per sq. inch)/ half span/ sag and temperature at max. load conditions; the same symbols with 2 as sufix are for stringing. Steel towers are used for long spans and are painted or galvanized. Examples for such construction are: the narrow base lattice type (support) with suspension type insulators, broad base tower (and cradle guard), standard double circuit towers. The foundations are excavated earth plus concrete. The tower legs may be fitted into position by templats. The different types of insulators that are found in transmission or distribution systems are the suspension, pin and post (vertical or horizontal). For higher voltage (over 50KV) suspension insulators are used as they are cheaper and lighter. The insulation of the line can be coordinated by using insulators with more units at some points where breakdown or flashover is to be avoided. The other components found on such insulators are arcing horns and grading rings. Pin type insulators are tested for transverse strength, suspension type are tested in pure tension. There are three kinds of vibrations of overhead line conductors. Firstly, the simple swinging of conductors in the wind which is harmless as long as the available clearance is sufficient to prevent flash over (sparking over) under condition of swinging. During sleet storms with strong winds, the second type of vibration is experienced which is a low frequency type (about 1 c/s), the amplitude is very large (about 20 ft). The last type of vibration is the high frequency oscillation (to 100 c/s) of about 1 inch amplitude. In this case the wind velocity is about 2 to 10 m.p.h. and steady. Under conditions of conductor vibration, the conductors at the supports (or clamps) may suffer fatigue which will cause eventually mechanical failure. The fatigue may be lessened by reinforcing the conductor for a few feet on either side of the clamp by binding metal rods (or a length of the same conductor) to the main conductor outside the clamp. The other method of protecting conductors from the vibration is through the use of dampers. The two examples are the use of a box which contains a weight resting on a spring and two weights attached to a stranded conductor (1 or 2 ft) which is clamped to the line (main) conductor.

The resistance of a conductor is given by $(\rho)(l/A)$, where ρ is the resistivity of material of the conductor, l is the length and A is the cross section area of the conductor, the units have to be compatible and yield the resistance in OHMS. This is the d.c. resistance value at 20° C. For a.c. systems, $R_{ac} = R_{d.c.}(1+Y_p+Y_s)$; where Y_p is a factor to allow for the proximity of the conductors and the Y_s is to allow for the skin effect at 50 or 60 c/s. $R_{\text{a.c. at temp T}} = R_{\text{a.c. @ 20}} [1 + \alpha t]$; where α is the temperature coefficient of resistivity per °C and t = T- 20°C. Temperature coefficient of resistivity for Al = .00407 per °C, for Cu = .004 per °C.

The inductance of a conductor $L = 4(10^{-7}) \ln (D/R')$ H/m; where D is the geometric mean distance (or the distance from the other conductor or where the inductance has to be calculated), $R' = r(e^{-1/4}) = r(.7788)$ is the geometric mean radius (radius of a fictitious conductor assumed to have no internal flux linkages but with the same inductance as the actual conductor of r radius).

The inductance of a conductor in a 3 phase transposed unsymmetrically spaced system = L =
$(L_a+L_b+L_c)/3 = 2 (10^{-7}) (\ln (abc)^{1/3}/R')$

where a, b & c are the distances between phases a-b, b-c, and c-a.

The inductance of 1- phase "A" conductor in composite conductors = $2\ (10^{-7})\ \ln\ [(D_{11}'\ D_{12}'..)..(D_{m1}'\ d_{m2}'..D_{mn})]^{1/mn} / [(R'D_{12}..D_{1m})..(R'D_{m1}..D_{m}\ \text{to}\ m-1)]^{1/m2}$ H/m
m is the total number of conductors in the "go" composite conductor, n is the total number in the "return" one. The mn^{th} root of the product of the mn distances between m strands of A conductor and n strands of "return" conductor B and is termed the geometric mean distance (GMD), the m^2 root of m^2 distance (the distances of the various strands from one of the strands and radius of same strand) is the geometric mean radius (GMR) or self GMD. The total inductance of the composite conductor = $L_A + L_B$.
Before covering the capacitance of the different configurations of overhead lines, let's define capacitor and capacitance. The former is an electrical device which consists of two conductors separated by a dielectric medium and is used for storing electrostatic energy. The latter is the ratio of the charge on one of its (capacitor) conductors to the potential difference between the two (2) conductors. The capacitance for a single phase transmission line (ignoring the effect of the ground) = $\pi\ \varepsilon o$ / [ln (h/r) +$(h^2 / r^2 - 1)^{.5}$] F/m, where r is the conductor radius and h is the distance between the centres of the conductors. If h is assumed to be much larger than r and the charge in coulomb/meter are uniformly distributed on the surface of the conductor, then the capacitance can be written as follows: $\pi\ \varepsilon o$ / ln h/r F/m. The capacitance of a 3 phase unsymmetrically spaced transmission line = 2 $\pi\ \varepsilon o$ / ln $(abc)^{1/3}$/r F/m; where a, b & c are respectively the distance between phases A-B, B-C & C-A. If a = b = c = h, then Cap. = 2 $\pi\ \varepsilon o$ / ln h/r.
For 3 phase, double circuit systems, the capacitance may be calculated for two configurations, hexagonal spacing and flat vertical spacing. Only the procedure is given hereafter: assume a charge distributed uniformly on the conductor surface q, calculate the potential on the conductor = $(q/2\pi\ \varepsilon o)$ ln d/r having $q_a+q_b+q_c = 0$, the capacitance/m/cond = q_a/v_a and per phase twice that per conductor.
Corona in transmission line is the ionization of air surrounding the power conductor. The process of ionization is cumulative and ultimately forms an electron avalanche. When the distance between the conductors is less than 15 times the radius of the conductor, flashover will happen before corona discharge. Thus corona can be defined as the self-sustained electric discharge in which the field intensified ionization is localized over a portion of the distance between the conductors (electrodes). The critical disruptive voltage is defined as the voltage at which complete disruption of dielectric occurs. The breakdown strength of air at 76 cm pressure and 25°C is 30KV (crest)/cm (21.1 KVrms/cm).
Eo = $m\delta\ g_o$ r ln D/r; where δ = (3.92 b)/(273 + T), b is the barometric pressure in cm, T is the temperature in °C, g_o is the breakdown strength of the medium in KV/cm, r is the conductor radius, D is the distance between the conductors, m is the conductor surface roughness factor (1 for clean smooth, .8 to .87 for standard conductors). As corona is initiated, a hissing noise is heard and ozone gas is formed which can be detected by its odour. The critical visual disruptive voltage = $m\delta\ g_o$ r $[1+(.3/(rd)^{.5})]$ ln D/r. The ions produced by the electric field result in space charges by the electric field result in space charges which move round the conductor. The energy required for the charges to remain in motion are derived from the supply system. This loss is referred to as corona loss. The corona power loss is directly proportional to the square of the difference between the operating voltage and the critical disruptive voltage in KV^2. The disruptive voltage is in turn proportion to the conductor radius. The

corona loss is, also, proportional to the square root of the conductor radius to the distance ratio. The factors affecting the corona loss are: electrical, atmospheric and conductor conditions. The electrical factor can further be classified into frequency (the higher the frequency - fundamental and third - present in the system when corona discharge occurs, the higher the corona loss), conductors height from the ground (the closer the conductor to ground, the higher the capacitance and the greater the corona loss) and finally the phase conductors configuration (the higher the field surrounding a conductor, the lower the critical disruptive voltage, the higher the corona loss). The lower the atmospheric factor, air density correction factor, the higher will be the loss. δ appears in the critical disruptive voltage equation (directly proportional to δ). Dust, rain and hail will reduce the critical disruptive voltage thus increasing corona losses. The factors affecting corona losses that are related to the conductors properties are: radius of the conductor (the larger the radius, the lower the loss), number of conductors per phase (bundling the conductors increases the self GMD thus increasing the critical disruptive voltage reducing corona loss), the shape of the conductor (with cylindrical shape the loss is less when compared to flat or oval), surface condition (the rougher the surface or the increase dirt increases the loss as the disruptive voltage decreased in value), heating of conductor due to load (may reduce or assist in reducing the corona losses). Thus the use of large diameter conductors with hollow shape and the use of bundled conductors will reduce corona losses. A typical transmission line may have under foul weather conditions losses as much as 20 times that under fair weather. The disadvantage of corona are power loss and interference with communication circuits. The advantage is the reduction of the wave front time (reduce the steepness) of an impulse wave (from lightning, for example) due to the increase of the capacitance of the line. A string of suspension insulators, will not necessarily have a uniform distribution of potential across them. If the capacitance that is formed between the insulator metal parts and the tower (metal) are reduced, uniformly distributed potential on the string of suspension insulators becomes feasible. The capacitance of each unit is known as mutual capacitance and is equal mc, the capacity to ground per unit is equal c. Then m = mc/c, if V is the operating voltage, then $V = V_1 + V_2 +..+ V_n$ where V_1, V_2, V_n are the voltages appearing across the insulator units starting at the cross arm downwards toward the power conductor. The voltage drop across the unit nearest the cross arm is minimum and it goes on increasing as the units getting further from the cross arm toward the power conductor. The string efficiency which is a measure of the utilization of the material in the string is given by voltage across the string divided by the product of the number of insulators in the string times the voltage across the unit near the power conductor. At any unit junction n in a suspension insulator $I_{n+1} = I_n+I_{cn}$ and $V_{n+1} = (V_n/m)+ V_n$. The conductor voltage, which is known, is also calculated in terms of voltage drop across first insulator from the cross arm (V_1) from which V_1 is calculated, then V_2, etc. are obtained. In order to reduce the stressing of the insulators closer to the conductor certain methods to equalize the potential across the units of the suspension insulator can be implemented. These methods can be summarized into selection of m (increasing the m ratio by using longer cross arms), grading of units (discs of different capacitive reactance, the maximum closer to the cross arm and the minimum closer to the power conductor, such that the currents flowing in their respective units produce the same voltage drop on each of the insulators units), guarding or grading ring around the power conductor/bottom unit (the pin to tower charging currents is cancelled through the use of the static shield). For a presentation of the potential distribution across the suspension string insulator assembly, click here.

I-1-3 Insulation coordination and over voltage protection: insulation coordination means the correlation of the insulation of the various equipment in a power system (power and distribution transformers, synchronous generators and induction motors, overhead insulators and underground cables, substation and padmounted switchgear assemblies) to the insulation of the protective devices used for the protection of such equipment from over voltages. The sources of over voltages in a power system are numerous and can be classified broadly into external and internal to the power system. When the voltage time curve of the protecting device is superimposed on the V/t of the protected equipment, a decision of whether the level (degree) of protection is adequate or not. The breakdown voltage for an insulator or the flash over voltage of a gap are function of the steepness of the front of wave and the peak voltage value of the voltage wave shape. The flash over may occur under any of the following conditions: front of wave flash over (the flash over occurred on that portion of the voltage wave applied-front-rate of rise), crest (flash over occurring at the peak voltage), tail (anywhere on the tail of the wave), as the issue of flash over is based on probablistic rather than deterministic base, the critical flash over means that the insulator will flash over for 50% of the application of the impulse wave (on its tai)l. The V/t curve is constructed from the above values the front of wave, crest, tail and critical flash over values, for the last 2 the points are the peak voltage values of the impulse wave vs time values of the flash over. There are two other curves that are of interest, the critical withstand (the maximum peak voltage having the same wave shape as the front, critical, etc. that would not produce a flash over) and the rated withstand. For lower voltages, up to 345 KV, over voltages due to circuit switching operations are not as dangerous as lightning on the equipment insulation; on the other hand, for voltages above 345 KV, the switching surges are more dangerous to equipment than those surges produced from lightning storms. For proper coordination the voltage class of the equipment has to be selected from which the basic impulse level or the flash over voltage values can be determined. Then, the protective equipment have to be selected to maintain the voltage as seen by the protected equipment under over voltage condition below the minimum flash over levels of the latter. The devices that may be used to provide such protection are: shielding (overhead grounding) wires, horn gaps, rod gap surge diverters, expulsion type surge diverters (protector tube), non linear gapped lightning arresters and metal oxide varistor lightning arresters (gapped or gapless). The use of ground rods and counter poise may be used to complement the installation of protection devices against overvoltages.

I-2 Subtransmission and distribution.

I-2-1 Transformers: transformers are used in unit generators to step up the voltage as well as transformer stations, distribution stations and substations to step down the voltage. In general, power transformers are built in three phase construction, while distribution ones can come as single or three phase constructions. Any transformer will be built from the following main components: the low-voltage winding (primary or secondary), the high voltage winding (primary or secondary), the iron core, the insulating material for the coil, air or any other medium), the tank (enclosure). The construction details will differ depending on the design of the core, number of phases, type of windings used, auxilliaries to be included in the assembly. In power systems analysis the important parameters that have to be known are: the nominal primary and secondary voltages; the percent impedance, resistance and reactance of each winding; the rated apparent power upon which the impedance is based (which is normally, the transformer rating). If a no-load or load tap changers are included with the transformer, the number of steps and reactance per step have to be provided. In an ideal transformer, the impressed emf on the primary winding (v1) is equal the induced counter emf in the winding (e1) neglecting the resistance.

v1=e1=N1df/dt, in the other winding mounted on the same core as the primary one the induced emf

(e_2) will equal the secondary terminal voltage (v_2) neglecting the winding resistance i.e. $v_2=e_2=N_2 d\phi/dt$.

Thus, $v_1/v_2=N_1/N_2$, $i_1/i_2=N_2/N_1$.

The impedance of the secondary winding referred to the primary winding (after which it can be added to the primary winding impedance) = $Z_2 (N_1/N_2)^2$. The following tests are performed on transformers: the no load (open circuited primary winding)) and the following data are obtained from such test: the secondary side voltage, the no load current and the power loss reading in watts (or KW); the short circuit (secondary winding short circuited) from which 3 values are obtained: the S.C. power loss in W (or KW), the short circuit current value as seen from the primary of the transformer (equal the rated current of the transformer if possible), the S.C. voltage circulating the S.C. current and finally the resistance of the windings using an ohmmeter @ 25 deg.C is measured. From the values obtained from such tests, the parameters of the transformers can be calculated. For the equivalent circuit of a single phase transformer, click here. The exciting current constitutes a fundamental and a family of odd harmonics (3rd, 5th, etc). On the other hand, the inrush current (transient exciting current) which flows through the primary of the transformer at time of energization is rich in 2nd harmonics (and other even harmonics). In steady state exciting current, the fundamental can further be resolved into two components one in phase with the counter emf and the other lagging the counter emf by 90 deg. The fundamental in phase component accounts for the power absorbed by hystersis and eddy-current losses in the core and is called the core losses component of the exciting current. Subtracting this component from the exciting current, the magnetizing current is obtained which constitute the component of the fundamental lagging the emf by 90 deg. and all the other odd harmonics. The transformer will see three types of inrush currents: initial, recovery and sympathetic. The first type occurs during cold load pick up and its magnitude varies depending on the size of the power system type of steel used in the transformer core, the saturation density level of the iron and the residual flux level. The duration of the presence of the inrush current is function of: size of the transformer bank, the resistance of the power system from the source to the terminals of the primary winding. The second type of inrush occurs when a fault occurs and then cleared, external to the secondary of the bank, at which the voltage will rerise to normal conditions (causing inrush current to flow). The last type occurs when the inrush of a transformer in process of energization finds another path to flow through which is another transformer that has been energized previously.

I-2-2 Overhead systems:

The major components of the overhead systems that will be covered hereafter are: poles, conductors, switches, insulators, capacitors, PLC and distribution automation. Poles as used in subtransmission and distribution systems can be any of the following: wood-pole structures, aluminum, concrete, fiberglass or steel. These structures are used to support electric lines (conductors, insulators, switches, pole mounted transformers, lightning arresters and if used shield wires). They have to provide electrical clearances and ample mechanical strength. Safe clearances have to be maintained if the conductor temperatures are elevated (as a result of the large currents flowing in the circuit), the conductor is ice-coated and subjected to blowing winds. Before covering the different types of poles, the different types of soils will be introduced. The simplest way to classify soils is cohesive or non-cohesive. An example of cohesive soil is clay as it is a fine grained soil, coarse grained soils are non-cohesive like sand. Further subclassification to cohesive and non-cohesive is possible based on the origin or method of deposition or structure of the soil. Soil structure may be classified as deposited (transported from their place of formation) or residual (formed by physical and/or chemical forces, breaking down parent rocks or soil to a more finely divided structure). Soils do not necessarily retain consistency at various depths, they are in layers of different thickness of unlike soils. Soils in general can be classified into 8 general classes from 0 to 8, 0 being the most solid (sound hard rock) like granite, basalt, massive limestone and 8 the softest like swamp and miscellaneous fills. Soil can be tested by soil test probes which give readings in LB-inch per probe pitch (the reading is at the end of the pitch). Another method of testing the soil is ASTM-1586 by which the classification of the soil is function of the number (count) of blows/ft. Soil can also be classified into: loose, dense, honeycombed, dispersed and composite.

•• Poles:

The most commonly used species of trees used for wood poles are: southern yellow pine, western red cedar, Douglas fir, western larch and jack pine. The factors that affect the choice of one type over the other are: the physical requirements of the poles, that are needed to construct the line, and the cost of shipment from the location where the species are grown. The proper treatment of the wood can improve, significantly, the service life of the poles as it prevents deterioration. Treatment can be conducted under or without pressure. Preservatives that can be used are any of the following: creosote oil, ammoniacol copper fatty acid, pentachlorophenol and chromated copper arsenates (CCA). Chemical preservatives are used to protect the wood from the attack of biological degraders like fungi, insects and marine organisms. Wood poles are commonly classified by length, top circumference and circumference measured 6 ft. from the butt (the other end). The lengths and the circumferences at the top varies in 5 ft and 2 inch steps, respectively. The circumference measured 6 ft from the butt end determines to which class (from 1 to 10) a pole, of a given length and top circumference, belongs. The classification from 1 to 10 determines the strength to resist the applied load at 2 ft from the top of the pole, class 1 being the strongest @ 4500 lb. minimum horizontal breaking load (M.H.B.L.) and 10 the weakest. Class 2 has 3700 M.H.B.L., class 3 has 3000 M.H.B.L., class 4 has 2400 and class 5 has 1900. The weight per pole for western red cedar varies from 880 lb. to 7500 for class 1 between 30 ft pole length to 100 ft. For class 2 it varies from 750 to 6550 lb. For northern yellow pine the weight varies for class 1 and 2 from 1279 to 8140 and 1082 to 6405 lb., respectively, for the pole length range of 30 to 90 ft. The maximum weight that may be installed on poles is function of the height of the pole, the class, the mounting distance from the pole top to the uppermost attachment, fiber strengths of poles, hoisting cable stresses and the linemen/ equipment to be on the pole at any time. Distribution circuit structures, generally, consist of single poles (wood), vertical or horizontal line post insulators (V/HLP) or pin type insulators with fiberglass support brackets or crossarms. Subtransmision lines operating at voltages of 138KV or lower can be built on single wood-pole structures. Fires on wood poles and crossarms can be initiated by leakage currents. When insulators on wood poles become contaminated by dust or chemicals, then light rain fog or wet snow moistens the insulators, the poles and the crossarms (if available), these conditions will cause leakage currents to flow to the ground. The leakage currents go to ground through a ground wire on the pole or the base of the pole. The flow of current is impeded by the dry areas on the assembly. When the medium in the dry zone (example air) is subjected to dielectric stress (voltage gradient) that exceeds the dielectric strength of this gap, an arc will be established. The arc, if close to combustible material like wood, it will ignite the wood in the dry area. The leakage currents can maintain the arc and the fire (after ignition).

Aluminum structures can be found when ornamental street lighting is used. The hollow-tubular street lighting poles give a pleasing appearance. The poles are lightweight, thus they are easy to handle. The supply to the lamps from the underground electric distribution systems are easier with the hollow poles.

The poles that are made from concrete are used for street lighting, distribution and transmission line. Concrete poles are more expensive than wooden ones, lower in insulation level, more difficult to climb, heavier to handle and more difficult to drill than wooden ones. The advantages of concrete poles are: their longer life and their availability on demand. Holes are provided to suit required pole framing, unused holes may be plugged with plastic caps. The poles are classified from A to J where A is the least strong 600 lb. and J the strongest with 4500 lb. ultimate load. The minimum required information to specify a round concrete distribution pole are: length in ft, top diameter, minimum raceway diameter, holes (spacing and diameter), apertures, grounding, bars (galvanized or coated), surface treatment, regular or prestressed class.
The hollow spun prestressed concrete poles have a high density concrete shell, completely, encasing a reinforcing cage containing prestressed high tensile steel wires. Prestressing produces poles with a high strength to weight ratios that is used for distribution lines. Square-tapered prestressed concrete poles are constructed by placing the stressed reinforcing material (in a form) and pouring the concrete into the form. For grounding purposes, a copper wire is usually casted into the pole. A plastic tube may be used to obtain a hollow pole. Fibreglass poles when compared to wood poles are immune to freezing, rotting, damage from nails and pecking of birds. Fibreglass poles are too expensive, but fibreglass components (like insulator supports) are reasonably priced. Fibreglass poles are used as streetlight poles supplied from an underground distribution system. This type of pole does not require painting.
Steel structures (towers) have been used extensively to support sub-transmission and transmission line conductors.
Wood is an organic material. The trunks and branches have, from the outside inwards the following: the bark, sapwood, heartwood and small core of soft tissue (in the centre). Trees are classified into the softwood (cedars, pines, firs, larches) and hardwood. Wood has independent properties in the direction of the tree's axes i.e. longitudinal, radial and tangential. The mechanical properties of wood include: the modulus of elasticity (stress divided by strain in the elastic zone of the curve), the modulus of rigidity and the Poisson's ratio = lateral strain / axial strain (all these properties can fall under the heading elastic properties), modulus of strength in bending, maximum stress in compression and the shear strength (strength of wood), sound velocity and damping capacity caused by internal friction. Wood defects can be related to either decomposition of wood fibre by fungi (decay) or to breakdown of cell walls as a result of applied stress beyond the yield stress of the cell of the wall material (mechanical destruction). Installed poles can be tested to determine the condition of poles. The ultrasonic method can be used at groundline or below. Ultrasonic technology deals with the behavior of high frequency sound (beyond the range of human hearing). Frequencies used for testing metallic materials range from 2.25 to 10 MHZ, those for testing wood and other nonmetallic materials range 25 - 100 KHZ. Ultrasonic pulses are produced by transducers and during the test the pulses are received by transducers (on the receiving end).
The types of ultrasonic pulses are:
- Longitudinal or compression pulses
- Transverse or shear (radial) pulses
- Surface or Rayleigh pulses
- Plate or Lamb pulses (in thin plates)
- Tangential pulses (in wood only).

The sonic velocity indicates the integrity of the pole. A higher sonic velocity indicates a longer life pole than a lower sonic velocity.

•• Conductors:

The wires and cables over which electric energy is transmitted are made of copper, aluminum, steel or a combination of Cu and steel or AL and steel. For overhead lines, hard drawn copper can be used. It is preferred over soft drawn or annealed as the treatment of the last two reduces the tensile strength of the wire from approximately 55,000 to 35,000 lb/sq.in. This is, also, the reason for eliminating soldering of hard drawn copper, as this causes the reduction in the strength of the hard drawn wire. Joints are made of splicing sleeves. Annealed or soft drawn copper is used for grounds or special applications where bending and shaping the conductor is necessary. Aluminum is widely used for distribution and transmission line conductors.

When the same sizes (cross section areas) of copper and aluminum conductors are compared, Al will have 60% of the copper conductor conductivity, 45% of copper tensile strength and 33% of copper weight. For the Al conductor to carry the same current as that of a Cu conductor its cross sectional area must be 66% higher than that of copper and in this case its tensile strength will be 75% and its weight will be 55% of that of the copper conductor. When Al conductor is stranded, the central strand is often made of steel to reinforce the cable. Reinforced Al cable called ACSR (aluminum conductor-steel reinforced) is suitable for long spans. Copperweld conductor which is a coating of copper securely welded to the outside of the steel wire. The layer of copper increases the conductivity and give a protective coating to the steel wire. The conductivity of copperweld conductors can be raised if the thickness of copper increases. The applications for copperweld are: rural lines, guy wires and o/h ground wires. Alumweld conductors are constructed from steel wire that is covered with aluminum to prevent the steel from rusting as well as to improve its conductivity. Concentric lay stranded conductors can be classified according to their flexibility class AA, A, B, C and D where AA is the most rigid, bare and used in overhead systems, C and D being the most flexible. The most important factors in sizing a line conductor are: the line voltage, the amount of power to be transmitted, the mechanical strength required, voltage regulation (drop through the line), power loss, span and total length of line. When conductors are connected to each other by connectors, the connection should provide an adequate current path under all expected operating conditions. The connection should withstand all the combined mechanical and electrical stresses (vibration, tension, shear, heat). Materials of conductor and connectors have to be compatible so load cycling (cold flow) would not produce hot spots or failures. Protection against weather conditions, like water stop and corrosion protection, is provided whenever possible.

The commonly used types of connectors are:

- Mechanical connectors: commonly used with copper conductors. Large spring-loaded pad is part of the installation when this type of connector is used with aluminum conductors, to avoid cold flow. Cold flow is produced when the aluminum conductor is heated in a copper connector and as Al expands 36% more than copper (co-efficient of expansion of AL and Cu: $12.8(10^{-6})$ and $9.4(10^{-6})$, respectively), the Al tends to flow out of the connector. When the connector cools down, the Al will contract and its diameter (inside the connector) will be slightly smaller than originally. This will cause an increase in the contact resistance which would lead to the generation of more heat (I^2R). During subsequent load cycles more Al will be flowing out of the connector, and even more heat generated at the connector.
- Compression connectors: they are used for Al and Cu conductors. The length of the connector is function of the ampacity and the tension. The right tools and dies must be used and the right number of crimps and pressure will ensure an efficient/ proper electric connection. Compression tools can be

classified into manual and hydraulic. Connectors when compressed over a conductor a specific range of % compaction must be attained in the range of 5 to 15 % of thhr conductor area. Excessive compaction will result in conductor deformation and light compaction may not provide sufficient pullout strength.
- Wedge connectors: is suitable for wide range of main and tap wire sizes. Aluminum should physically be placed above copper when both materials are used in one connection.
- Stirrups: are used to provide a connection zone (area) for the hot line clamp away from the main line so that arcing will not damage the main conductor. They can be classified into wedged and bolted, the first being more reliable.
- Hot line clamps: they are used to connect equipment onto the main overhead lines. They make connecting and disconnecting easier.

To minimize cold flow any or all of the following should be observed: use compression type aluminum connectors, use Belleville washers, the aluminum connectors must have substantial mass to run cool and the contact area between the conductor strands and the connector is to be maximized. When exposed to air, an invisible oxide film is produced (which is corrosive resistant). It has an insulating property and has to be removed when connections are made.

•• Switches:

Switches can be divided into four general classes. Air switches, oil switches, vacuum switches and SF6 switches. Air switches can be further classified into: circuit breakers, air break, load break and disconnect switches. Oil switches can be circuit breakers or oil circuit reclosers. Vacuum can be a vacuum circuit breaker or a vacuum recloser. SF6 can be a circuit breaker or a circuit switcher or a recloser. Circuit breakers are mostly used in indoor substations (unit, transformer or distribution) or in outdoor (on structure, as stand-alone) installations. Overhead switches can also be classified according to their method of operation i.e., manual vs. manual/motor and also according to the possibility of remote/ local operation or only local operation of the switch.

Overhead switches can also be classified according to their type of installation: vertical (tiered), horizontal or riser pole or in line (mid span openers), triangular or poletop. Switches can also be classified according to their type of break i.e. vertical, side or double.

When interrupted, the arc is formed between the metal horns of the circuit carrying the current. The distance between the horns increases as the switch continues to open. The arc is cooled by wind and extends in length until extinction. Air break switches are usually mounted on substation structures or on poles and are operated from the ground level. The switches are operated by a handle connected to the rod, extending from the switch to a level close to the ground where the opening/closing operations are performed. Air break switches can be automated (motorized) to allow for remote operation. For different switch configurations sketch, click here.

Oil switches are high voltage switches whose contacts are opened in oil. The high pressure oil bubble is formed and the arc runs in a mixture of hydrogen (in both molecular and atomic states), carbon and metal (copper) vapour. Oil switches can be single or three phase, electrically operated, with handle for manual operation. The electric motor would require low voltage supply for its operation. In general, these switches can be operated remotely (automatically) through the use of current, voltage or time sensitive devices. These switches are used to interrupt inductive currents and capacitive currents including capacitor banks. When capacitors are switched, back-to-back, damping resistors are added in series with the arcing contacts of the switch to limit the inrush currents. The types of mountings are: crossarm, double crossarm, broadside-mounting, substation or single pole mounting.

Disconnect switches are air break switches, not equipped with arcing horns or other load break devices.

The different configurations of disconnect switches, as used on overhead systems, are: the branch feeder style, crossarm vertical, crossarm inverted, station vertical, station inverted and main feeder style. When portable load break tools are used in conjunction with these switches, switching the following elements is possible: transformers, lines, cable and capacitors (with certain limitations). These switches are defined by the following parameters: insulation ratings (the nominal voltage in KV and the BIL in KV), rated continuous current in amperes, leakage distance in inches, dry arcing distance, disconnect gap in inches and cantilever strength of insulator in LBs. In general, load break tools can be classified into a load interrupter tool and paralleling tool. The paralleling load breaking tool will create a temporary bypass jumper across the disconnect (in parallel with the permanent tap connection). After the blade of the tool is closed, the permanent tap can be disconnected. The load can then be dropped by opening the blade of the tool. The tool operates by simple disconnect stick. The load interrupter tool is defined according to its nominal voltage and its interrupting capability (nominal and maximum). The load break tool, usually, has an anchor to hang on the attachment hook of the disconnect (cutout or power fuse- for that matter) and a pull ring hook to engage the switch pull ring. Generally, the load break tool is attached to a universal pole. After connecting the tool to the disconnect as previously mentioned, the universal pole is pulled downward (firmly and steadily) and as the tool is extending to its maximum length, the disconnect is opened and the current is diverted through the tool. At a predetermined point in the tool opening stroke, its internal trigger trips, the charged operating spring is released, the internal contacts are separated and the circuit is interrupted. The tool has to be reset for the next operation.

Load break (interrupter) switches come in single and three pole configurations. When current is interrupted, the arc is confined and extinguished in the interrupter (no external arc interruption or separate device is required). These switches can interrupt line currents (load splitting, load dropping), transformer load and magnetizing currents, cable charging and load currents. Generally, the blades are made of hard-drawn copper with silver-to-silver contacts, the silver plated stationary contact may be formed of copper and include a tapered profile to improve blade closure. The arc extinguishing process is similar to the one which occurs when an indoor load break switch has to break the current and extinguishes the arc in the arc chute or arc tube. With the switch in the fully closed position, current flows through the copper blade and the silver contacts (the interrupter is, totally, out of the circuit). As the blade begins to open, the current is transferred to the interrupter by wiping action between the shunt contact and the interrupters external contact. After which, the main current carrying contacts part. The next step is the opening of the internal contacts of the interrupter by the blade cam. The arc inside the interrupter is extinguished by thermal action and the deionizing gases generated from the liner and the internal design of the interrupter. Exhaust is quiet and flameless and is vented through the exhaust cap. Load break switches can be motor operated for remote close / open operation. The air break switches have a gas (or vacuum) counterpart where the arc is extinguished in SF6 poles or vacuum bottles. There are two major constructions for gas filled overhead switches which are: one with visible break and one without. The visible break will have an SF6 bottle where the contacts break, afterwich the arc extinguishes and a disconnect switch (interlocked with the SF6 contacts) is used to provide the visible break (the disconnect is in series with the SF6 pole). The other type will have the load interrupting/ switching contacts and operating mechanism contained in a hermetically sealed welded tank. The motorized operating mechanisms are classified into rotating and reciprocating types.

•• Insulators:

The function of an insulator is to separate the line conductor from the pole or tower. Insulators are fabricated from porcelain, glass, fiberglass, polymer or silicone. Insulators can be classified into pin, post and suspension. They can, also, be classified according to the method of attaching the conductor to the insulator i.e. clamping or tieing. The properties of any insulator can be classified into: mechanical, electrical, environmental and maintenance. The mechanical characteristics can further be classified into: everyday loads, exceptional loads, design loads, cyclic loads, torsion and static loads, safety factors, single or multiple insulator strings, long term strength. The electrical criteria are further divided into: clearances, BIL, power frequency flashover or withstand voltage (dry and wet), steep front wave, power arcs, leakage distance, contamination performance. For the environmental characteristics, the following are important: ageing under UV and dry arcing, type of contamination, corona, RIV, washing, corrosion of end fittings and temperature range. The final property of an insulator is maintenance, it comes down to ease or difficulty of handling or the need for special precautions. In general there are three lines of defence for an insulator: hydrophobicity, self cleaning and track / fire resistance.

Porcelain insulators are made of clay. Special types of clay are selected and mixed mechanically until a plastic-like compound is produced. The clay is then placed in moulds to form the insulators. The moulds are placed in an oven to dry the clay. When the insulator is dry, it is dipped in a glazing solution and fired in a kiln. The glossy surface produced from this process makes the surface self-cleaning. Cementing several shapes can make available large porcelain insulators. Cement growth, which may result from chemical reaction between the cement and the metal parts, can cause stresses that can crack the insulator.

Glass insulators are made from sand, soda ash and lime. The materials are mixed and melted in an oven until a clear plastic-like product is produced. This product is then put in a mould and is allowed to cool. The final step is putting glass insulator in the oven for annealing.

Fiberglass insulators (fiberglass rods with flexible skirts) are made up of fiberglass treated with polyester resin or more commonly with epoxy resins. Rubber-like compounds are applied to the rods to fabricate suspension, dead-end and post type insulators. The rubberlike compound can be EPDM (Ethylene Propylene Diene, Modified) polymer or silicone elastomer. EPDM is applied by injection as well as silicone. EPDM and silicone come in many different fomulations. Silicone is based on siloxane resin (Polydimethysiloxane). The base molecule consists of a chain of alternate oxygen and silica atoms with organic methyl groups attached to the silicone atoms.

The properties of silicone to be used as insulators in power distribution systems are: high tear strength, high tracking and erosion resistance, has to be highly hydrophobic, it has to recover quickly from any temporary hydrophobicity loss and has to resist UV aging. Continuous corona effect, close proximity of silicone insulators to large quantities of water vapour, spraying the insulator with salt water and rapid buildup of deposit on the surface of the silicone will have negative impact on the performance of the insulator. The degree of permanent loss of hydrophobicity is different for each of the conditions aforementioned. It became obvious that certain tests should be performed on the materials applied to the rods to be able to anticipate its performance over its long expected life time, these tests are:

- Surface, which can be evaluated for tracking and arc resistance. Surface erosion is mainly linked to UV radiation, corona and is enhanced by humidity and salt, thus testing for this effect for outdoor insulators is extremely important. Surface erosion should be differentiated from pitting erosion (damage in depth of insulator over a small area).

-Tracking wheel (Merry-go-round test) is the the track and fire resistance test of the specimen insulator. Tracking wheel test procedures vary because of the following: spray solution ingredients, volume of

spray, test voltage, maximum allowable current (limited by the fuse or C.B.), rotation speed, test specimen and orientation.
-Contamination (salt and fog) test is used directly on insulators, the important factors in such test are: the salt concentration, test voltage, shape and creepage distance of the insulator.
The following points are worth investigating for the bulk material used as insulators for installation outdoors: thermal endurance, mechanical creep, long-term dielectric break down, partial discharge and as a complementary test to the partial discharge x-ray radiation test for larger cavities and voids. Polymer concrete and rigid polymer is one homogeneous body providing the necessary electrical and mechanical properties for the application. Metal inserts can be potted into polymeric materials during the cure period. Epoxies can be formulated for track and fire resistance and provide the high strength out of the popular polymer materials: polysteres, acrylics and epoxies.
•• Reclosers and Sectionalizers:
Reclosers can be classified according to their interrupting medium (oil, vacuum or sulphur hexafluoride). Reclosers are used on overhead distribution systems to split a long feeder and to minimize the tripping of the transformer station feeder breakers. Co-ordination is needed between the feeder breaker and the reclosers. A sectionalizer is another device that can be found in overhead distribution systems, it must, always, be backed up by a recloser of the proper size. The sectionalizer is installed on taps or branches off the main lines or somewhere along the feeder. When a fault occurs beyond the sectionalizer, the recloser will operate. If a fault is permanent, the sectionalizer will count the number of operations of the recloser and trip/lock itself, after a pre-determined number. The recloser continues on its final operation, restoring power up to the sectionalizer. Other recloser/sectionalizer combinations depend on the sensing of voltage and time co-ordinated, rather than counting the number of operations. Reclosers are designed to interrupt and reclose alternating current circuits. The number of reclosings is adjustable up to 4 times. It recloses after a pre- determined time. After the fourth reclose, the device locks itself in the open position. It has to be reset through an operator and then closed. A fuse link interrupts temporary and permanent faults alike. Reclosers give temporary faults repeated chances to clear or be cleared, by a downstream fuse or sectionalizer. The control of reclosers is achieved either hydraulically or electronically. Recloser ratings range for series coils, from 5 to 1120 A and for non-series (current transformers are used), from 100 to 2240A. The minimum pick-up for all ratings is set, usually, to trip instantaneously at twice the current rating. The points of installation of reclosers depend on the amount of exposure of the line, the operating experience and the degree of importance of not tripping the transformer station feeders. Reclosers can be considered equivalent to the following: a circuit breaker, overcurent relay, reclosing relay. To define a recloser, the following data, as a minimum should be available: rated maximum voltage, continuous current, BIL, maximum interrupting capacity, voltage withstandability and the duty cycle of the reclosing philosophy.
•• Fuses for distribution transformers:
In distribution systems, three phase transformers and three phase banks (i.e. 3 single phase connected to provide a delta or a Y 3-phase configuration) are common. In general, the protection of the power transformers is provided through the use of protective relays (o/c or differential and over current ground) and gas relays. The distribution transformers are protected by fuses (current limiting and expulsion types). The distribution transformers are either ovehead (pole mounted) transformers or installed in above or below grade vaults or pad mounted. The connection and protection to each type differ significantly. Pad mounts can be classified into radial feed and loop feed. The pole mounted

transformers have ahead of them current limiting fuses and distribution cutouts with fuse links with speed T or K as defined in ANSI C37.100 other speeds are also available to achieve proper co-ordination between the fuses and upstream/downstream protective devices. Medium voltage fuses (2.4 to 72kV) can be classified according to the following, they either fall under the distribution fuse cutouts or power fuses. The power fuses can further be classified into expulsion type and current limiting. Distribution fuse cutouts were developed for use in overhead distribution circuits (a connection to distribution transformers, supplying residential areas or small commercial/industrial plants). Pole mounted capacitor banks, used for voltage regulation or power factor correction, can be protected by such fuses. A distribution fuse cutout consists of a special insulating support and fuse holder. The disconnecting fuse holder engages contacts supported on the insulating support and is fitted with a fuse link (with speed K-fast - or T-slow - as defined in ANSI 37.100). The operation of the fuse is governed by two curves: the minimum melting and the total clearing. The fuse holder is lined with an organic material. In fuse cutouts, the interruption of an overcurrent takes place inside the holder. The gas ionized (liberated), when the liner is exposed to the heat of the arc (as a result of the melting of the link), is then deionized (at current zero). Power fuses have characteristics that differentiate them from distribution fuse cutouts, these characteristics are: they are available in higher voltage ratings, they can carry higher load currents, they can interrupt higher fault currents and they can be installed indoors. Power fuses consist of a fuse holder, which accepts a refill unit or fuse link. The power fuse (expulsion type) interrupts currents, like the distribution cutout. The current limiting type interrupts overcurrents when the arc established by the melting of the fusible element, is subjected to the mechanical restriction and cooling action of powder or sand filler, surrounding the fusible element. Current limiting fuses can reduce the mechanical forces exerted on the components (in series) from the source up to the fault point due to the peak short circuit current. They can, also, reduce the thermal overloading due to the integration of the short circuit current over the period of the fault existence. They may impose an overvoltage condition on the equipment connected due to the current reduction effect (forcing current to zero before natural current zero, gradually). The typical ratings for the fuse/fuse holder combination are: nominal voltage, maximum voltage, BIL, current rating, speed and interrupting rating.

•• Overhead (Pole-mounted) transformers:

These transformers can be fastened directly to the poles, hung from cross arms, mounted on racks or platforms or mounted on brackets attached to the poles. The KVA ratings for such transformers are low i.e. 167 or 250. The pole mounted transformers can be installed in clusters of 3 transformers attached to the supporting brackets of which the latter are attached to the poles. The high voltage bushing with the clamp type connector is connected to the primary (medium voltage circuit) and the low voltage cables are connected to spade type connectors. The pole mounted transformers use oil as the insulating material. They are installed in many configurations. In general, these transformers are connected to the primary circuit through a current limiting fuse and a fuse cutout. To protect the transformers against lightning or voltage surges, the primary of the transformer will have a lightning arrester connected across it and the ground. There is another type of pole mounted transformers which is the completely self protected one (CSP). Primary fuses and lightning arresters are included with the transformer, thus there is no need to any external protective device except for a current limiting fuse.

•• Framing and Guying of poles:

Pole class and guying are function of loading on the pole. Loading on poles are calculated for crossing of railways, waterways & highways; crossing of other other power or communications lines and pole angles or dead endings. The loading calculations will include: ice and wind medium or heavy loading,

transverse wind loading, pole line angle changes, longitudinal loading (along the conductor line), vertical loading.
Framing means the dressing of the pole with the insulators that will carry the conductors. Just to list a few examples: single phase primary circuit with the insulator on the top or side of the pole, 3 phase triangular armless with 1 insulator on the top and 2 on the sides, 3 phase triangular armless with the 3 insulators on the sides, vertical dead end and double circuit framing.
A guy is a brace or cable fastened to the pole to strengthen it and keep it in position. Guys are used wherever the wires tend to pull the pole out of its normal position and to sustain the line during the abnormal loads caused by sleet, wind, and the weather. Guys counteract the unbalanced forces imposed on the pole by dead ending conductors, changes in conductor sizes/types/tension, angles in the distribution lines. Guy assemblies can be classified into: anchor (down), span, head, arm, stub and push. For common pole guying configurations sketch, click here. The main components of the anchor guy assembly are: galvanized machine bolt with nut, locknut, square curved galvanized washer, galvanized steel guy wire, porcelain guy strain insulator, prefabricated guy dead-end grips, plastic guy guard, angle thimbleye, eyenut, steel anchor rod, power installed screw anchor. Holding strength is function of the guy wire, anchor rod/ anchor hub/ anchor area/ soil classification.
•• Capacitors in distribution systems: Capacitors are found in power systems, at various locations. They are applied on systems with a wide range of voltages. Capacitors come in ratings that range from a few KVA capacitive to a few MVA capacitive. There are many reasons for applying capacitors at the transmission, distribution or utilization levels. The capacitors are applied to electrical systems: to improve power factor, increase capacity of line (upstream the point of application of capacitor), offer voltage regulation (maintain network voltage within the acceptable limits). Capacitors are generators of positive reactive power, it is usually considered as devices that supply lagging current (rather than taking leading current). The loads on any power systems are either resistive, reactive or a combination of both. The reactive power is a lost power and it keeps circulating between the inductance and capacitance of the system. The generated power has to provide for this non useful power requirement. The apparent power can be expressed as S = VI, the active power (which is used to generate work, light or heat an area, rotate a motor,..etc.) = VI cosØ, the reactive power =VI sinØ. Idealy, capacitors are used to develop reactive power as near as possible to the point of consumption. Series and shunt capacitors (in a power system) generate reactive power. This increases the capacity of the system and reduces the losses because of the improved power factor and voltage drop along the line / system. The reactive power is either proportional to the square of the load current in series capacitors or the square of the voltage in shunt capacitors. Series capacitors are rarely used in subtransmission and distribution levels and, also, at the loads due to the following: installation cost is higher than the corresponding shunt capacitors, it has to be selected taking into consideration all additional loads to the circuit (in series) with the series capacitors, it may create certain disturbances (ferro resonance and subsynchronous resonance). Shunt capacitors are placed in banks and can be connected in any form: grounded star, ungrounded star, double star neutral floating, delta, double star neutral grounded. Shunt capacitors are primarily used to improve the power factor, to improve the voltage level in an O/H line system with a high power factor, and to reduce the line losses. If series capacitors are used the main reasons would be: to reduce the voltage fluctuations, to improve the voltage level in an underground or O/H line with normal and low p.f. Capacitors are sometimes used to control transient recovery voltage levels and rates of rise i.e. limit it, when breakers are switched. The bank is built up of series and parallel elements, of which the total voltage (line to ground) is applied to the terminals of the capacitor

bank. The loss of an element inside the capacitor increases the voltage across the group. The results of such incident cause overheating and consequently failure of the unit. There are, generally, a minimum number of units required to limit the voltage increase to 10% above nominal when an element fails. Usually there are two levels of protection for large banks. The first relay is set to operate an alarm in case of loss of one unit (element) and the second relay to trip the bank circuit breaker when the 10% allowed overvoltage is exceeded. When capacitors are used in transformer stations, the following protection is provided: over/under voltage, neutral voltage displacement, time delay (auxilliary), over current and earth fault. The capacitors may be of the switched or the non-switched type. The factors affecting the selection of one type over the other are: the minimum loading and the maximum voltage of the feeders at the substations. In general, long and heavily loaded feeders will have pole mounted non switched (fixed) capacitors at strategic locations, to compensate for approximately 30% of the load KVAR.

•• A brief introduction to programmable logic controllers (PLC):

PLC are used in almost every industry to control the process and the operation of equipment. Despite the vast range of configurations and levels of sophistication that specific applications demand, there are some basic elements common to all programmable logic controllers (PLCs).

A PLC is a solid state device that works on conventional microprocessor computer principles. The microprocessor is programmed to respond as a programmable controller which continuously and sequentially performs certain functions. PLCs receive input from a variety of switches and sensors, make decisions based on input status plus program logic and, finally, write outputs to affect equipment control.

The control function that a PLC system performs has three basic elements: the sense, the decision and the control. Input from the field is generated by push buttons, limit switches, relay contacts, selector switches, and other sensors and switches. Outputs are sent to the field to control motor starters, circuit breakers, valve actuators, solenoids, and relays. The decisions a processor makes are executed by manipulating the registers which reside in the PLC processor. (A register is a small portion of memory that can be used by the processor to store different kinds of information.)

This manipulation does not occur unless a user developed control program is stored in the processor memory. The control program is developed using ladder diagram programming. In the ladder diagram all I/Ps are shown as contact symbols and all O/Ps as coil symbols along with an associated number which is the address. These address numbers reference either the location of the external I/P and O/P connections to the PLC or the internal relay equivalent address within the processor. The major modules that build a PLC are: the processor, the different types of the input/output modules, the process control module, the stepper motor controller, the different types of interface modules, the perpheral devices which constitute: the loader/monitor, process control station, CRT programmers, hand held programmers, tape loader and the racks. Only typical processors and input/output modules will be covered hereafter.

The processor:

The processor is a self-contained device which houses the control processor, the communication ports, user memory, scan processor, registers, fault monitoring circuity, real-time clock and status light emitting diodes.

The principal function of the processor is scanning. More specifically, the processor reads inputs, consults the ladder diagram, and updates outputs accordingly. The longer the program, the longer the scan time.

Another reason for a slow scan time is fragmented registers - registers containing both input and output data. Registers hold in their memory the changing information upon which the processor bases its decisions. Registers can hold the status of digital I/O (for example, 16 bits) or a single number representing a timer, a counter or any data value.
Input and output devices connected to a PLC are assigned address numbers. The registers could be assigned and used for digital I/O, internal relays, data storage or as register modules. The limitation on the usage and addressing of registers is based on the processor design.
Processor memory can be classified in a number of ways, including PROM (programmable read only memory) factory programmed executive program, which makes the micro-processor perform as a programmable controller, and RAM user memory used to store the ladder diagram. Random access memory is volatile and needs battery back-up. It is used for data handling and variables storage, including the status of timers, counters, and digital I/O. Set points and tables can also be stored in these registers.
Some types of processors gave a user memory RAM and UVPROM (ultra violet programmable read only memory). A RAM/UVPROM processor not only provides the capability of storing regular ladder rungs in UVPROM but also allows the programming of critical circuits in an unchangeable format.
LED indicators on the front of the processor will signal run (processor operating properly), halt (processor is not scanning), memory (processor detected an error in user memory), force (one or more inputs or outputs have been forced to ON or OFF), I/O (malfunction occurred within the I/O registers or external system), battery low (back-up battery is low), write protect (part or all user memory is protected from alterations). The processor is mounted in the CPU slot of a digital or register rack assembly.
INPUT/OUTPUT MODULES:
The input/output modules used to interface between the field and the processor are numerous but there are some basic configurations. A broad classification for these modules is whether or not they can be classified as intelligent.
•Digital input modules. These modules are capable of receiving signals from four, eight, or twelve field input devices (switches and sensors) or five volt dc devices. Inputs are either electrically isolated or not isolated from each other. Each of the optically isolated inputs has a LED indicator on the front of the module which illuminates on receiving an ON signal from the field I/P device.
•Digital output module. These modules are capable of driving loads such as motor starters, solenoids, and pilot lights. These outputs may or may not be not be electrically isolated from each other. The front cover of such modules could give up to three LED indicators: one illuminate when the processor issues a command to energize the output, another when the I/P voltage is provided on the O/P terminal, and the third could be a blown fuse indicator. These modules are installed in I/O digital rack assemblies.
•Analog input modules. Thers modules are inserted in any slot of a register rack except the CPU or into the register slot of a digital rack. The analog module is made up of several subsystems: the analog to digital converter, the input multiplexer, the on-board microprocessor, the auto-calibration system, the dc-to-dc converter, signal and power isolation circuitry. This type of module is capable of recieving a number of channels (up to four) of high level analog input signals. The signal is then converted through the analog to digital converter subsystem and then inputted to processor.
•Analog output modules. These modules can be plugged in the same location as analog input modules. This type of module is made up of digital to analog converter, sample and hold circuit, on-board microprocessor, dc-to-dc converter, signal and power isolation circuitry.

The module is capable of generating a number of analog output signals for controlling equipment action (valves, rheostat,..).
For further information: An introduction to PLCs, part I. An introduction to PLCs, part II. An introduction to PLCs, part III. An introduction to PLCs troubleshooting.

Distribution system automation:
In any distribution system automatically (remotely) controlled, certain elements have to exist: controlled equipment/devices (like switches, breakers, pad mounted switchgear, tap changers), control station (where the man machine interface equipment are located: work stations, terminals, RTU and software), the controlling equipment like the RTU/sensors interface and the motors/springs mechanisms) and finally the communication medium (power line cariers, packet radio, fiberoptics). The presentation of this subject will be based on a hypothetical system representing the equipment in the transformer/ distribution stations, the components of overhead and the underground distribution systems. A typical transformer station may have the following elements: a high voltage disconnect switch (eg. 230KV, 200A, vertical break), a power transformer/oil immersed/forced cooled (eg. 100/125 MVA 230/27KV) with on load tap changer and gas pressure relays, line- ups of switchgear assemblies (eg. SF6 circuit breakers, 27.6KV, 2000 Amps), relay panels (including bus differential protection, transformer differential protection, back up protection, feeder protection -or located on the switchgear assembly, transmission line impedance relays, reclosing relays, breaker failure protection schemes, remote tripping for terminal breakers), battery/charger system with protection indicators and metering. The distribution system, overhead and underground may include the following: motor operated sectionalizers, motorized load break switches, reclosures, capacitor switching devices, faulted circuit indicators (o/h & u/g), padmounted transformers/switchgear, pole mounted transformers, lightning arresters, overhead conductors and underground cables. Data to be collected and equipment to be controlled can be classified broadley into digital (on-off, 1 or 0) and analog (continuous) processes. The number of points to be monitored or controlled and the number of channels required to build a system wide SCADA are to be known in order to achieve an optimum system with provision for future expansion. Other automated tols that are found integrated in a DA system are automated mapping/facility management, primary analysis software, transformer load management. A few of the pitfalls of automating are: hardware interface incompatibility, communication protocols are different, the available polling techniques and the limitations when considering expansion oradditions in hardware ports and communication medium bandwidth. The required indications from the load break switch are whether it is opened or closed (through the use of a dry "C" contact - N.O. and N.C. contacts), close or open the switch (through contacts in the closing coil and trip coil of the switch). To monitor the transformer and control the fans, analog and digital inputs and outouts would be required. Examples for such points are: the change in the step of the load tap changer and the indication of such steps, the temperature of the oil and the remote indication of windings thermometers (on the transformer tank), the indication of the fans running (one or two banks), the gas relay contacts (energized or denergized), the oil level indication, forcing the fans to run remotely (or to stop). The main medium voltage circuit breaker should be closed and opened from the conrol station (through contacts in the close & trip coils of the C.B.), the indication of the main contacts position within the breaker i.e. closed or opened, the indication of the C.B. in its cubicle (ie. in the connect, disconnect or test positions). The feeder breakers would have the same states/positions/conditions monitored as the main breakers. The power measurements and protection should also be indicated on the terminals in the control room. Examples for metered analog quantities and digital control are: currents (demand and

instantaneous in the the three phases), the real and reactive power, the voltage, the relays operation and if available the faulted current level, the reclosing scheme status, whether enabled or disabled, the programming of the digital relays when it comes to setting the pickup levels/curve shape/time delays, resetting the relays, monitoring the battery system, all the alarms (for levels that exceed or decrease below the set limits) eg. overloads, undervoltage etc. For the distribution system, the degree of complexity and the functions of operation/monitoring would be based on the philosophy to be adopted. The general applications will be given hereafter, the strategic switches can be remotely motor operated (thus 2 digital inputs to indicate position and 2 digital outputs to open and close the switch are required), sensors to indicate at the control station the voltage and current values, thus for each location monitored, 2 (per phase or for 3 phases) analog inputs would be required to monitor each phase in sequence and report the levels, if capacitors are present on the distribution system, the level of the reactive power/voltage should be available at the control stations complete with means to operate and indicate the position of the capacitor associated switches, should the system have faulted circuit indicators, remote indication of the status of the F.C.I. is required (through a digital input), for motor operated pad mounted switchgear remote control and indication ofthe different switches (taps) is required through the use of digital inputs/outputs, loading of transformers on the system can be indicated through the SCADA system if sufficient communication channels and hardware points are available. With underground systems, the most probable communication system will be the Radio Frequency as hard communication wires may not cover the full subdivision. Other options may be (depending on availability) fiberoptics, copper wire drops or powerline carriers.

The distribution automation and control functions can be classified into load management functions, real time operational management functions and remote metering functions. The load management functions may include: discretionary load switching, peak load pricing, load shedding and cold load pick up. The second set of functions may have: load reconfiguration, voltage regulation, transformer load management, feeder load management, capacitor control, dispersed storage and generation, fault detection/location/isolation, load studies, condition or state monitoring and remote connect/disconnect of services.

•Discretionary load switching or customer load management activity; this activity is appropriate to loads like water heating, air conditioning and thermal storage heating. It involves direct control of such loads (at individual customer sites), from remote control central location. The purpose of such action would be to reduce the load on a particular substation or feeder if it becomes overloaded (and such loads are part of the connected load to such station or feeder).

•Load (peak) pricing activity; this activity would allow the implementation of peak load pricing programs through the remote switching of meter registers.

•Load shedding activity; it permits the rapid dropping of large blocks of connected load under certain pre-defined conditions, according to an established priority basis.

•Cold load pick-up activity; it entails the controlled sequential pick up of the previously dropped loads.

•Load reconfiguration activity: it involves the remote control of switches and breakers to permit routine daily, weekly or seasonal reconfiguration of feeders/feeder sections. The purposes of such actions are to assist in performing the routine maintenance, taking advantage of load diversity among feeders, to reduce losses or serve more loads.

•Voltage regulation activity: it allows the remote control of selected voltage regulators (if present on the system), together with distributed capacitors to effect coordinated system wide voltage control from a central location.

•Transformer load management activity: this function enables the monitoring and continuous reporting of transformer loading data and core temperature, in order to prevent overloads, burnouts or long time abnormal operation. Reconfiguring the network loading can assist in achieving longer life from distribution transformers and can improve outages scheduling (to replace defective components).
•Feeder load management activity: it allows the reporting of feeder loading and sections thereof. The purpose of this activity is to equalize load distribution over several feeders thus reducing unnecessary line losses. Fault detection, location and isolation: sensors located throughout the distribution network can be used to detect and report abnormal conditions, locating and isolation of faults can be performed based on this data. Thus proper sectionalization and circuit reconfiguration can be performed efficiently.
•Conditions and state monitoring: this function involves real-time data gathering and status reporting. Examples are: status of load break/disconnect switches and recloseures, MW and MVAR of monitored circuits or loading on distribution stations.
•Remote service connect/disconnect services: it permits remote control of the switches to connect or disconnect an individual customer's electric service from a remote site.
•Automatic customer meter reading: the four main elements: the transmitter, the receiver, the communicating media and the power supply. The communicating media can be line of sight (RF systems), fibre optic, dial up or dedicated phone lines, power line with associated wave traps. The purposes of such function are more accurate data gathering regarding a service or a customer consumption of electrical power, reduction in the cost of reading/maintaining the meters over the traditional methods.

I-2-3 Underground system:
•• Underground cables:
Underground cables are classified according to their voltage class i.e. .6 KV, 15 KV, 25 KV, 35KV,... The subclassifications function of the voltage class are: the insulation type (solid type, oil filled), number of conductors per cable (1 or 2 or 3 or 4), insulation thickness (100 % or 133 % the rated voltage), neutral size for cables with phase and neutral conductors (full vs. 1/3 phase capacity), neutral conductor shape (concentric vs. solid or stranded round), jacket type (sleeved, encapsulated or cable in conduit). They consist of three essential parts: the conductor for transmitting electrical power, the insulation medium required to insulate the conductor from direct contact with earth or other objects and the external protection cover to protect against mechanical damage, chemical or electrochemical attack. Copper and aluminum conductors are found in underground distribution cables. The conductor can be solid or stranded. The stranding class indicates the degree of conductor flexibility (AA, A, B, C, D - AA being the most stiff and D the most flexible). The strand is made up of a number of wires. The wires in a stranded conductor are twisted together to form lays. The successive layers are usually stranded in opposite direction. The stranded conductor construction is more flexible than solid conductors. Another advantage of stranded cables is that breaking and kinking of conductor in the dielectric are eliminated. In general, the cables size l/0 to 4/0 will have 18 or 19 strands, 250 to 500 MCM 35 to 37 strands, 600 to 1000 MCM 58 to 61 strands and 1250 MCM 91 strands. Cable size can be given, for example, 19/0.1, where the first is the number of strands and the second is the diameter of each strand in mm (or in AWG). Stranded conductors can be classified into concentric, compressed or compact. The main dimensions that define a cable are: the aluminum or copper conductor cross section area, the diameter over the insulation, the diameter over the insulation screen, the diameter over the concentric neutral or tape (if applicable) and the diameter over the jacket. The jacket thickness may be

given or can be calculated The standards that govern the material, construction and testing of cross linked thermosetting- polyethylene insulated wires and cables are ICEA (insulated Cables Engineers Association) S-66-524, CSA standard 22.2 No. 0.3.

The insulating materials used with cables have the following properties: high insulation resistance, high dielectric strength, good mechanical properties, it should resist chemicals surrounding it and it should be non hygroscopic, i.e. moisture and water resistant. The materials used in cables are: rubber, polyvinylchloride, polyethylene, oil & impregnated paper.

Rubber materials can be classified into:

-Vulcanized rubber: in its natural form it is considered an insulating material. The draw back is its property of absorbing moisture. The result of this draw back would be the loss of its insulating property. Hard or vulcanized rubber is produced by mixing rubber with 30% sulphur, other softeners and antioxidation or other compounding agents. The end result is an insulating material which is rigid, resilient and does not absorb moisture.

When it comes to synthetic rubber materials (elastomers) known as rubbers, they can be classified into: general purpose synthetics which have rubber like properties and special purpose synthetics which have better properties than rubber with respect to fire and oil resisting properties. The four main types are: butyl rubber, silicone rubber, neoprene and styrene. Rubbers are hydrocarbon polymeric materials similar in structure to plastic resins. An elastomer is defined, per ASTM, as a polymeric material which at room temperature can be stretched to at least twice its original length and upon immediate release of the stress it will return quickly to approximately its original length. Certain types of plastics can approach the rubberlike state (polyethylenes). Others have elastomer grades, for example olefins, styrenes, fluorplastics and silicones.

-Butyl rubber: Also referred to as isobutylene- isoprene elastomer is copolymers of isobutylene and about 1 to 3% isoprene. It is similar in many ways to natural rubber. It has excellent resistance, but it resists weathering, the sunlight and chemicals. This type of insulation, in general, has lower mechanical properties (tensile strength, resilience, abrasion resistance and compression set) than other elastomers. It has excellent dielectric strength, thus it can be used for cable insulation, encapsulating compounds and a variety of electrical applications.

-Silicone rubber: is one member of the family of silicone elastomers. The elastomers are polymers composed basically of silicon and oxygen atoms. They can be classified into general purpose, low temperature, high temperature, low compression set, high tensile-high tear, fluid-resistant. They are the most stable of all elastomers, they have good resistance to high and low temperatures, oils and chemicals. The silicone rubber can be vulcanized by cross linking the linear chains and can flow under heat and pressure. It resists heat, most chemicals (except strong acids and alkalies).

-Neoprene: also known as chloroprene, it is the first commercial synthetic rubber. It is chemically, structurally and mechanically similar to natural rubber. It resists oils, chemicals, sunlight, weathering and aging. It is consumed by fire but it is non-combustible. It is relatively low in dielectric strength.

-Styrene-butadiene elastomers: sometimes called, Buna S are copolymers of butadiene and styrene. The grades with styrene over 50% are considered plastics. A wide range of property grades exists by varying the relative amounts of styrene and butadiene. Styrene content varies from as low as 9% to up to 40%. They are similar in many ways to the natural rubbers.

Polyvinyl Chloride (PVC): it is a polymer derived, generally, from acetylene. It can be produced in different grades depending upon the polymerization process. PVC is inferior to vulcanized rubber with respect to elasticity and insulation resistance. PVC when used with cables has to be processed with plasticizer. PVC can be classified into general purpose, hard grade PVC (has less amount of placticizer) and heat resisting PVC.

Polyethylenes: these thermoplastic resins include low density polyethylene (LDPE), linear low density polyethylene (LLDPE), high density polyethylenes (HDPE) and ethylene copolymers. The advantages to be gained with polyethylene are light weight, outstanding chemical resistance, mechanical resistance and excellent dielectric properties. The basic properties of polyethylenes can be modified with a broad range of fillers, reinforcements and chemical modifiers. Polyethylenes are considered easy to process: injection molding, sheet film extrusion, coating extrusion, wire and cable extrusion coating, blow molding, rotational molding, pipe and tube extrusion and others. The basic building blocks of polyethylene are: hydrogen and carbon atoms. These atoms are combined to form ethylene monomer, C_2H_4 i.e. two carbon atoms and four hydrogen ones. In the polymerization process, the double bond connecting the carbon atoms is broken and these bonds reform with other ethylene molecules to form long molecular chains. High density polyethylene resins have molecular chains with comparatively few side chain branches. Its crystallinity is up to 95%. Low density polyethylene resin has crystallinity from 60 to 70%. Linear low density polyethylene resins has between 60 and 75%. The degree of cristallinity is a measure of the density of the resin. With the higher densities, the heat softening point, resistance to gas and moisture vapour permeating and stiffness are high. On the other hand, increased density will result in reduction of stress cracking resistance and low-temperature toughness. The range of density for LLDPE resins is 0.915 to 0.940 g/cm^3, for LDPE resins 0.910 to 0.930 g/cm^3 and HDPE 0.941 to 0.965 g/cm^3.

The last type of insulation to be covered here is the impregnated paper. A suitable layer of paper is lapped on the conductor depending upon the operating voltage. It is then dried by the combined application of heat and vacuum. This process can be carried out in a sealed steam heated chamber. After the cable is dried, the insulating compound is forced onto the paper cable and all the pores are filled with this compound. After this last step (impregnation) the whole assembly is allowed to cool under the compound so that the void formation due to compound shrinkage is minimized.

The insulation resistance for a single core cable is given by the following ($\rho/2\pi$ l) ln (D/2r) where ρ is the resistivity or specific resistance of the dielectric, r is the radius of the conductor, l is the length of the cable and D is the diameter of the sheath or concentric neutral.

Stress and capacitance of single core cables: the capacitance in cm / cm length is given by ε / (2 ln (D/d)); where d is the conductor diameter. This equation can be written as 0.03888 ε/(log D/d) μ F/mile length.

The stress at a distance x from the axis is given by E/ (x ln D/d), the stress is maximum at the conductor and is equal (E/r)(ln D/d) or (2E/d) (ln D/d), the stress at the lead sheath is (2E/D) (ln D/d); where E is the peak voltage of the conductor (potential difference between the core and the sheath).

It can be seen from the above that the ratio of the stress at the conductor to that at the sheath is D/d. There are two main methods by which a more uniform distribution of stress may be achieved: by the introduction of intersheaths and with layers of insulating material with different dielectric constant. These methods are primarily used in high voltage cables.

Power factor of single core cable, suppose that the dielectric has a resistance ρ which is independent of the stress and may be considered as constant throughout the cable; upon the application of an alternating voltage of frequency f, there will be an in phase current equal the voltage divided by the resistance of the insulation per cm length. The resistance = ρ dx/(2π x 1) ohm/cm. The losses with alternating currents are caused by absorption phenomena and is usually much less than those caused by d.c. The charging current = ω C V; where C is given by ε/2ln D/d cm/cm and leads the voltage by 90 degrees. The total current I (assuming a parallel circuit presentation of the dielectric) is the vector sum of V/R and ω CV and leads the voltage by an angle $\tan^{-1} \phi = 1/\omega$ CR. The conductance (reciprocal of R) of the cable per cm length is G = cosϕ (ω C). This measurement indicates the quality of the insulation. If the angle ϕ is 90 (or close to) i.e. cos ϕ is zero or close to (is equal to tan δ ; where δ =90-ϕ) the cable is considered in good condition. The dielectric loss is V/R=VG= ω CVϕ. The power factor of the dielectric materials vary with stress and temperature. It increases with the increase of any of these two variables i.e. stress or temperature. The voltage to break down a certain insulation depends upon many factors such as duration of application, shape of electrodes, temperature, pressure, the presence of moisture and gaseous spaces. The most common ways of failure in cables are: coring (or tracking) and thermal instability. The first has the progressive coring starting at the conductor or the sheath and ultimately bridges the electrodes (conductor & sheath). The second occurs when the power factor increases so rapidly with the rise of temperature in such a manner that a small rise in temperature increases the dielectric losses by a greater amount.

The electrical characteristics of cables: the resistance is given by $R_{ac} = R_{dc} (Y_s + Y_p)$; where R_{ac} is the ac resistance, R_{dc} is the dc resistance, Y_s is the correction for skin effect and Y_p correction for proximity effect. The inductance is given by .460 log (GMD/GMR) = 0.2 ln (GMD/GMR) mH/ Km. Generally, the difference between overhead and underground secondary (low voltage) systems is that the last will have only one cable, from the distribution transformer, serving as distribution and service entrance conductor. In an overhead service from a pole line, the two functions are, in general, more separate. Regarding the installation, the Canadian Electrical Code Part I has to be consulted and the local and Provincial authority having jurisdiction should, also, be consulted for assurance of compliance with all these required regulations. The assemblies found in low voltage (secondary) underground cables are the simplex, duplex, triplex and quadruplex. The simplex is a one conductor, the duplex is one insulated (or insulated and jacketed) conductor and a neutral conductor, the triplex is two insulated (or insulated and jacketed) conductors and a neutral conductor, the quadruplex has three insulated (or insulated and jacketed) conductors and a neutral conductor. The neutral conductor is insulated like the line (phase) conductor but may have a reduced rating ie. its size (cross sectional area) is smaller than the line conductor size. These cables will usually have copper or aluminum conductor with XLPE insulation and PVC jacket. The single conductors are twisted together to form any of the above mentioned assemblies. The length of the lay will be between 25 and 60 times the insulated conductor diameter. There is another design which and is designated as USEB 90. It is built as follows: conductor(s), XLPE insulation (without jackets or coverings, these cables are assembled-twisted together), helically applied a layer of bare annealed copper wire covering the cables (this is the neutral assembly) & PVC outer jacket. The neutral conductor will be rated 100% or 60% i.e. having equal conductance to the line conductor or 60% (reduced) of the line conductance. The standard colour coding is as follows: simplex: black; duplex: black and white; triplex: black, black (with a stripe) and white; quadruplex: red, black, blue and white.

Production tests are, usually, performed on completed lengths or on samples taken from the completed reel. Specific tests are done, only, on the complete reels like D.C. conductor resistance test, A.C. high

voltage test, D.C. high voltage test and insulation resistance tests. These tests may also be required but not necessarily on the complete reels: physical dimensions of the cable components, cold bend test and low temperature impact test.
The conductors used in medium voltage cables are either copper, compressed, stranded, annealed, uncoated copper, or solid or compact stranded with strands of aluminum. The most commonly used insulating materials in the medium voltage (primary) range are the cross-linked polyethylene and the ethylene propylene rubber which are rated for continuous operation of 90 deg C. The concentric neutral or shielded tape (the metallic insulation shield) is applied on the insulation semiconducting shield. The concentric neutral is wound helically and is made of annealed uncoated copper wires, usually. Under the concentric neutral, an equalizing tape (annealed untinned copper tapes), each is applied in opposite direction to the other. There are a few ways and materials that are used as cable jackets. Briefly, they are sleeved or encapsulated, the material is PVC or linear low density polyethylene (LLDPE). Certain cables are used without any jackets. The PVC covering of cables comes as a sleeved jacket and a separator between concentric neutral and the jacket. The LLDPE covering comes either as encapsulated jacket or sleeved. When LLDPE sleeves are used, a water blocking agent is used to prevent the longitudinal travel of water in the space betwen the jacket and the insulation shield. The same agent can be used with encapsulated jackets to fill the voids between the jacket and the neutral. In general for the same size cable, the sleeved cables are more flexible and is easier to handle than the encapsulated ones. For crosslinking of polyethylene there are a few methods in use today: peroxide systems, radiation and silane bridges formation. The curing of the extruded cables takes place in air at ambient temperatures, in a hot water bath or in a steam room. The failure in cables with this insulating material can be attributed to the water absorption property of XLPE. When the cables are subjected to stress (i.e. under voltage) and water is on the outside or the inside of conductor, transparent tree-like imperfections are formed. These water trees are initiated in voids or contaminants in the body of the insulation. Some of the factors that contribute to water tree growth in extruded insulation are voltage (stress), water, contaminants and imperfections, temperature gradient and aging. The strandseal (the liquid filling the spaces between the strands in the conductor area) characteristics are: high viscosity at overload temperature to ensure that the strandseal will not flow from the conductor, good low temperature properties (i.e. compound fracture under low temperature while bending the cable should not happen), compatible with metals of the conductors & conductors semiconducting shields and adhere to conductor over a broad range of temperatures. All these cables have the ability to be directly buried, layed in PE conduits and then buried, pulled in PVC conduits or pulled through conduits encased in concrete. When the concrete encased designs are used, manholes have to be constructed and should have sufficient space to cut, splice and pull the cables. For a cross section of a single conductor cable & examples for laying/burying cables, click here. They should be strong enough to withstand the loads above them without collapsing. In general, manholes, handholes and vaults are to be designed to sustain all expected loads which may be imposed on the structure. The vertical and/or horizontal design loads shall consist of dead load, live loads, equipment load, impact, load due to water table or frost and any other loads expected to be imposed on and/or adjacent to the structure. The manholes are generally built of reinforced concrete or brick and the covers are made of steel. The opening leading from the street to the manhole chamber is called the chimney or throat. An opening having a minimum diameter of 32" is usually provided. This opening has to be large enough for a man to enter on a ladder and also to pass the equipment needed for splicing and testing. The pulling rope is attached to the cable by means of a woven cable grip, sometimes called basket grip, or by means of a clevis or eye. To prevent injury to the

cable by scraping on the manhole frame or at the duct opening, a feeding tube (guiding tube) is sometimes used. To protect the cable from excessive tension during pulling in, the cable is lubricated with a compatible material to the jacket. The cable is drawn into the duct by means of a winch or capstan The winch is usually mounted on a truck or a portable cable puller located near the manhole or the riser (pole) conduit, at pulling end. The following production tests are performed on the completed reels: partial discharge level test, central conductor DC resistance test, AC high voltage test, insulation resistance test, DC high voltage test. The following tests can be performed on the full length or on a sample of the cable: physical dimensions of the cable components, cold bend test, low temperature impact test, jacket electrical integrity test, strand-fill compound production test (water penetration and high temperature drip tests). The following physical properties of the cable components (conductor shield, insulation, insulation shield and the jacket) are checked: for the conductor shield: volume resistivity, elongation at rupture, aged water boil, voids and protrusions irregularities and brittleness temperature; for insulation: tensile strength, elongation at rupture (aged and unaged), dissipation factor, hot creep test, solvent extraction (for XLPE), voids and contaminants; for the insulation shield: volume resistivity, elongation at rupture (aged), water boil test, voids and protrusions irregularities, strippability at room temperature and at -25 deg C; for the jacket: tensile strength, elongation at rupture (aged and unaged), heat distortions, heat shock and absorption coefficient; for the completed cable: insulation shrink back (for certain insulating materials eg. XLPE) test and structural stability.
Sizing and temperature limits of cables: there are several reasons why cables should not run too hot: differential expansion may create voids with resulting ionization, thermal instability and for oil cables, the expansion of oil may burst the sheath or the oil may lose its viscosity and drain away from higher levels (the same can apply to the water blocking agent in solid dielectric cables). The method of determination of cable rating is based on OHM's law thermally rather than electrically. The formula that gives the heat transfer across a layer (between opposite faces) with a temperature gradient is: heat flow in thermal watts = temperature difference in deg C/ thermal resistance in thermal ohm The thermal ohm is defined as the difference of 1 deg C between opposite faces of 1cm (volume) that is produced because of the flow of 1 watt of heat (1 watt= 1 joule/ sec.). The thermal resistivity depends upon the material of conductor, insulation, protective covering and the ground. A common empirical formula (relation) for the determination of the continuous rating of cables is:

$I = [\ \theta\ /R(G'+n\{G_b\ (1+\lambda\ ) +(G_a+G_d+G_s+G_e)(1+\lambda\ +\lambda\ 1)\}]^{.5}$

I: current in conductor in A

θ : conductor temperature rise above ground ambient (deg C), conductor temp. - ambient temp.

λ : sheath loss factor eg. = 0 (when there is no sheath).

λ 1: armour loss factor eg. = 0 (for cables with no armour).

G': thermal resistance between conductor and sheath or concentric neutral - thermal ohm/cm (deg C cm/watt) eg. for EPR = 400 deg C cm/W.

G_s: thermal resistance between armour and cable surface (deg C cm/watt) eg. = 0 (when no armour exists).

G_a: overall thermal resistance between outer surface of cable and inner surface of duct (deg C cm/watt) eg. = 0 (when cable is directly burried).

G_b: thermal resistance between sheath (or C.N.) and armour (or outside surface of cable) in

deg C cm/watt eg. = 0 (neglecting losses in C.N.), = 350 (for PE) or 650 (for PVC).
G_d: thermal resistance between inner and outer surface of duct (deg C cm/watt) eg. = 0 (for directly burried) and = 85 for concrete .
G_e: thermal resistance between outer surface and ground level (of soil) in deg C cm/watt, eg. = 100 (range 90 to 1000 deg.C cm/W).
R: ac resistance of conductor at conductor temperature i.e. 90 deg C in ohm/cm eg. for Al = .0275/10000 ohm/cm.
n: no. of cores eg.1 or 3.
conducor temperature: 90 deg C
ground temperature: 30 deg C
ambient air temp: 40 deg C
The thermal resistance is given by : g l/ A; where g is the thermal resistivity of the material, l is the length of the heat flow path and A is the section through which heat flows. The thermal resistance for a single conductor cable is (g (100)/2π) (ln R/r) thermal ohm/cm; where R is the inner radius of the sheath, r is the radius of the conductor. The thermal resistance of the ground is (g(100)/3π)(ln 2h/R) thermal ohm/cm, where h is the depth of the cable axis below the ground level.
Measurement of L, C & tan d: Bridges are used for the measurement of inductance, capacitance and loss (dissipation) factor. The dissipation factor or tan δ is a measurement of the quality of the insulation. The lower the factor value (eg. .001to .02), the better the insulation. Starting at 0.08 and higher is an indication of the insulation degradation. Note that cos ϕ = tan δ = ω CR; where C is the capacitance of the insulation and R is the resistance of the insulation (the insulation is presented by a series combination of resistance and capacitance). The bridges that are used in practice are: Maxwell's inductance, Wien's & Schering's capacitance bridges (give also tan δ) and combined Maxwell/Wien bridge for L, C and tan δ .
The accessories that are used with cables to complete an underground installation or a connection to riser (or dip) poles are: cable terminations, cable splices, elbows to connect to the primary of the transformers (vault or pad) or switchgear.
The use of cable terminations is dictated because of the following:
-due to the abrupt change in the continuity of the cable shield the electrical stresses increases (the termination will reduce this stress).
-the need to increase the creepage distance between the live conductor and the ground (or neutral or shield).
-the need to prevent moisture ingress into the cable.
-overhead line vibrations have to be prevented from being transmitted to the underground cable.
The different types of terminations are: the fully taped, molded stress cone and tape, one piece molded, porcelain terminators, potheads and heat shrinkables.
Cable splices are used for the following reasons:
-continuation of all cable components is to be maintained.
-to provide protection against entrance of water and other contaminants into the cable.
-to provide mechanical support to the cable.
When making a splice, the following conditions have to be fulfilled:
-voids should not be introduced.
-the in line connector has to be of the right size.

-the right tool and compression force has to be used to crimp the connector to the conductor of the cable.
-the applied insulation thickness should not exceed 1.5 times the cable insulation, to avoid overheating of splice.
Tapped splices, heat shrinkables and cold shrinkables are commonly used. The major components of molded cable splices are: cable adapters, splice housing, interference fit, conductor contact, molded conductive insert, grounding eye, aluminium retaining rings and aluminum tube. For typical tapped splice, click here and for a cable termination components click here.
Elbows or separable connectors (as sometimes called) are built to ANSI/IEEE standard 386. The basic components for such a configuration are: the elbow and the bushing insert that goes into the bushing well. This construction is classified into the dead break (i.e. it cannot break current, it has to have no current flowing, to be able to break the elbow from the insert- it is usually rated 600 A) and load break one that is usually rated 200A. The major components of a dead break elbows are: the semiconducting shield, the insulating plug, the compression connector, the molded body, the insulation, the cable adapter, the capacitive test point, the elbow semicoducting insert and the rubber cap over the test point. The load break has the following components: the grounding tab, the insulation, the semi conducting insert, the locking ring, the probe (typically field replaceable, tin-plated copper with abelative material arc follower), semiconducting shield, the pulling eye, the connector and the test point (if available). The design tests performed on these elbows are: corona voltage level, ac withstand voltage, dc withstand voltage, impulse withstand voltage, short time current, switching test, fault closure test, current cycling test for insulated and uninsulated connector, accelerated sealing life, cable pull out operating force test, operating eye test, test point cap operating force test, test point cap operating withstand test, test point capacitance test, shielding test, accelerated thermal test, interchangeability test. For the components of a typical elbow and insert, click here.
Faulted circuit indicators which can be installed in padmount transformers or switchgear can be classified accordingly: manually resettable, high voltage, current resettable and timed resettable. The basic idea of operation is that if a fault to occur downstream this device all the indicators ahead of the fault will operate or set (as the fault current is flowing through them) and all the ones downstream the fault will not operate. For the manual reset types, the intervention of the operator is required to reset the device. For the high voltage type, when the supply is restored i.e. the voltage is available again on the section (circuit), the device resets. For the current type, after repairs have been done, the current that is flowing in the circuit reaches a minimum pre-adjusted value (eg. 2 or 3 amp.) will cause the device to reset. For the timed one, after four hours, let's say, it will reset automatically. These four hours are usually factory adjustable. When an indicator operates, it will show the section of the buried cable that may be faulty. Certain designs come with attachments to alleviate potential nuissance resetting or setting like the effect of proximity of cables, inrush currents when energization of transformers or due to reclosing actions of reclosures or station circuit breakers and due to feedback.
If the cable is directly buried, excavation has to be kept to a minimum and the location of the fault has to be indicated as accurate as reasonably possible. Thus fault location equipment has to be used. The main methods that may be used are: Murray loop test, fall of potential test, dc charge and discharge test, induction test, impulse wave echo test and arc reflection.
-The Murray loop test can precisely locate the fault if its current is more than 10 mA i.e. for a battery with 100V, the fault resistance can be as high as 10 Kohm. The sensitivity is function of the detector used. In its simplest form, the faulty cable is looped to an adjacent sound conductor of the same cross

sectional area. Across the open ends, a galvanometer is joined and parallel with it a resistance box with two sets of coils. The d.c. supply is connected to this arrangement. When the galvanometer pointer is balanced (because of adjustments to the resistance box), the fault location is found by: distance to fault = (a / a + b)times loop length.

-The impulse wave echo (Cable radar): this method is based on the principle that a pulse propagating along a cable will be reflected when it meets an impedance mismatch. For a cable of uniform dielectric, the pulse reflected at the mismatch is displayed on a CRT at a time delay directly proportion to the distance of the mismatch from the test end (irrespective of the conductor size) and is given by X = (t_1/t_2) times cable route length; where t_1 is the pulse time to fault (or mismatch) and t_2 is the pulse time to far end of cable. This method can be generalized and through the use of generators that give pulses of short duration and low voltages being transmitted through the cable, any deviations (cable start, splices, faults and cable end) will produce reflections. These reflections will be displayed on the CRT of the measuring device. The limitation of this method is when the fault resistance is high (higher than ten times the cable characteristics impedance which varies in the range of 30 to 50 ohm). With high impedance faults, burning the fault into a lower resistance fault and cable radar method is used to obtain the fault location.

-Arc Reflection: this method is considered as a combination of cable radar and surge pulse methods. The latter being a generator of high voltage pulses that are sent throughout the cable and produces arcing at the fault location, part of the pulse energy is reflected to the cable start where it is partially reflected into the fault. This process continues until the capacitively stored energy is exhausted. The observation on a CRT of the spacing of the reflections will indicate the fault location.

Route tracing: self contained instruments are available for tracing the routes and the depth of hidden or buried cables. The location of underground cables is based on the principle of the concentric electromagnetic field surrounding a current carrying conductor. To identify and locate a cable, a predetermined frequency current from a generator is transmitted along the cable. The resulting magnetic field is then explored by means of an inductive probe or detector rod with the integral search coil and receiver. Theq are equipped with to give audio and visual signals. If the searching devices can detect power frequency, the high frequency generator.

Padmounted Switchgear:

These switching assemblies can be classified into air insulated, oil sealed insulated, or SF_6/load break switches and vacuum fault interrupters. Typically, for the air insulated type when the separable connectors are in place, the construction will have all energized parts enclosed in grounded (shield) enclosure (dead front). Verification of the open switch (visible break) is possible through plexiglass viewing windows. The three phase gang operated switches in the assembly are operated without having to open the cable compartment. The 600 A deadbreak bushings are externally replaceable. The unit will have parking stands, replacemant fuse storage pockets, ground pads for grounding provisions, door retainers, latching (3 point) arrangement, fuse viewing windows, lifting provisions, fault indicators and floor cover (if required). The oil filled units will have a fill plug, a drain valve, the oil gauge, the cable entrance, the steel tank, the spring operator, the mechanical interlock over the fuse compartment, grounding provision, parking stands and the hinged cover. The major elements for the third type (SF_6/Vacuum) are: the heavy gauge enclosure, sealed switch compartment, operating handle (for manual operation), fill valve/gas pressure gauge, electronic control package (pad-lockable), electronic load tap trip adjustments (knobs, push buttons), spring assisted switch operator (with marked position indicator), provisions for padlocking, cable entrance bushings, phase indication labels, parking stands,

deadbreak elbow connectors, door latches, hinged doors with stoppers, viewing windows, ground lugs, deep well low current (eg. 200 A) bushings, mechanical trip and reset lever, provisions for door padlocking, motor operator/RTUs. The motor/RTU installation would provide remote operation of the switches (from a control station) or local operation (motor operated). With the availability of sensors/RTU in the pad mounted switchgear assembly, the remote indication of the load levels and faults (currents) at the control station may assist the operators in running the system more efficiently with less down times and higher levels of supply continuity.
The production tests run on such assemblies are: continuity test (to assure correct internal connections), hi-pot (dielectric), pressure test (to assure tank is sealed), the protective (electronic o/c) device characteristics curve and leakage tests (if required). To remotely operate and indicate with pad mounted switchgear and underground distribution systems, the following elements are to be part of the switchgear unit: one set of three current sensors on the load side of each interrupter (or switch), source side PT with 120 V (for example) secondary voltage, radios/modems or the required communication equipment, connector for remote antenna (if applicable), local interface in the controller (status, control switches, displays), local communication port to setup/updating software/troubleshooting/report generation using a laptop. Should ducts be, already, installed the use of fiber optics communication network would be the most suitable (over other means of communications: RF, PLC, ..., etc.). Fibre optics is immune to electromagnetic and radio interference, thus it can be placed in ducts containing high voltage Cu or Al cables (i.e. 15, 27.6 kV). The elements that are needed to build a fibreoptic network beside the cable are the transceivers with the serial and optical ports (LED transmitter and photodiode receiver), the RTUs, optical splitters, multiplexes and modems.
I-2-4 Lightning and lightning arresters:
•• Insulation levels of structures: in an overhead (o/h) distribution system, the components that provide the support and adequate insulation (against rated and overvoltages) to the installed equipment and conducrors are: the poles (wood, aluminum, concrete, fibreglass, steel), insulators (eg. post - vertical line or horizontal line, pin type), crossarms or support brackets (wood or fibreglass).
The equipment and conducrors seen in an overhead system are: pole mounted (overhead) transformers, lightning arresters to protect the overhead equipment and the line itself, load break and disconnect switches, fuses (expulsion and current limiting types), O/H bare primary conductors (for example 556.6 MCM aluminum), O/H secondary cables (multiplex types). If the BIL (basic impulse level) of the structure is exceeded by a direct or induced lightning stroke, flashover of the feeder (line) occurs. The BIL of the structure is the sum of the insulator plus all of the insulation levels of the path of the flashover to the ground. Accurate BIL measurements for structures are obtained by testing the structure with a surge generator. For all practical purposes, estimates of BIL can be made using insulator catalogue values. The use of metal hardware will cause a reduction in the BIL level of the structure, also guy wire, location of the neutral wires and reduced clearances will cause the overall BIL of the structure to be reduced. The use of anything other than wood poles like aluminum or concrete will lead to a lower structure BIL. As can be observed from above, the use of ungrounded crossarms, in series with the insulation, improves the total BIL. There are certain curves that show the sparkover voltage in kV, versus the length of the crossarm (only) or the combined insulators plus the crossarm. One finding of these curves is that the BIL level of wood increases with the increased length of the un-bonded wood crossarms. An average value is 40 kV/ft. of crossarm, based on a minimum length of 10 ft. It is worthwhile mentioning here that the response of insulator strings to switching and lightning impulses is independent of pollution, only the gap distance and the electrode shape are significant. On the other

hand, the response of the insulator strings to power frequency is a function of the degree of pollution, the flashover value will be halfed when the insulator becomes extremely polluted from being lightly polluted. Most distribution pole structures have a BIL from 150 to 400 kV. External insulation is defined as the distance in atmospheric air and the surfaces in contact with the atmospheric air of the solid insulation of the equipment which are subjected to dielectric stresses (also to the effects of atmospheric and other external conditions like pollution, humidity, vermin,...etc.). Insulation strength increases with absolute humidity up to the point where condensation forms on the insulator surfaces. It decreases with a decrease in air density. The estimation of the strength can be based on the average ambient conditions at the particular location (temperature, air pressure and absolute humidity). Reduction to the withstand voltage is possible due to snow, ice and fog.

The geometric configuration of the insulation in service consists of the insulation and all the terminals attached to it. The dielectric behaviour is function of the insulating and conducting materials. The insulation configurations can be classified accordingly:

- Three phase: having three phase terminals, one neutral terminal and one ground.
- Phase to earth: a three phase insulation configuration with two phase terminals are disregarded and the neutral terminal is grounded.
- Phase to phase: a three phase configuration where one phase terminal is disregarded. The neutral and ground terminals are, also, disregarded.

Causes of overvoltages:

The internal causes producing a voltage rise are: resonance, switching operation, insulation failure, arcing earths (grounds). The external cause is lightning.

Resonance:

Resonance can occur at the fundamental power frequency (60 or 50 c/s) or any higher harmonic order like 5^{th} or 7^{th}...etc., harmonics. It may occur when an inductance is in series with a capacitance and is excited by the a.c. source with frequency equal to the natural frequency of the L.C. circuit. The voltages appearing across the inductor or the capacitor may be higher than the exciting voltage. The cable connected to the transformer in a distribution system is a good practical example of such conditions. Voltage magnification at Resonance = Voltage Across L or C / supply voltage. The conditin of resonance is $C = 1/\omega^2 L$; where L is the transformer leakage inductance, C is the cable capacitance to ground, ω is equal to 2(3.141)(f) and f is the frequency of the fundamental or the harmonics. Resonance can happen at a harmonic rather than the fundamental for example when a lightly loaded cable is having a higher order harmonic like the fifth. The voltage appearing across the capacitance to ground (i.e. across the cable) divided by the exciting voltage is equal $1/\omega CR$ or $\omega L/R$; where R is the combined resistance of the transformer and cable. Ferroresonance can happen when switching a single phase of a three-phase lightly loaded cable / transformer combination.

Switching operations:

When switching takes place (energizing or de-energizing of a load), transients are generated and the system is stressed. As the circuit is built up of resistance / inductance / capacitance (lines, cables and transformers) and because re-distribution of energy in the circuit cannot happen instantaneously, transients will occur. In other words, the magnetic flux linkage of a circuit cannot suddenly change, the voltage across the capacitor cannot change abruptly nor its energy stored in the associated electric field and because energy conservation must always be preserved, transients are generated. Slow front

overvoltages are usually associated with line-energization and re-energization. More will be said about this subject in chapter 5 "Transients in power systems".
Insulation failure or arcing grounds (earths):
Under insulation failure (single phase to ground) conditions, the voltage on the unfaulted phases will go up as much as the value equal to the line-to-line voltage for unearthed (isolated) neutrals or delta connected systems. For solidly grounded, the phase voltage will remain unchanged under single phase to ground. For effectively grounded systems (i.e., $X0/X1<3$ and $R0/X1<1$ for any condition of operation, where X0, X1, R0, are zero sequence reactance, positive sequence reactance and zero sequence resistance, respectively), the voltage on the unfaulted phases can reach 80% the line to line voltage.
The arcing earths can lead to insulation failure, due to the build up of voltage across the unfaulted phases, as a result of the extinguishing of the arc at zero volt of the faulty phase. Flashover may result between the phase conductor and ground, this causes further disturbances (transients) on the systems other two phases. If oscillations take place between the capacitance of the line and the inductance of the machines, the voltages still go higher, causing more flashovers and higher voltages on the phase conductor. This can finally lead to the failure of the insulator (a single phase or phase-phase to ground fault).
Lightning phenomena:
Some of the accepted facts and phenomena regarding thunder clouds are:
- the height of the cloud base above the surrounding ground level may vary from 500 to 30,000 ft. (150 to 9,000 meters). The height of the charged centres are between 1,000 to 5,000 ft. (300 to 1,500 meters)
- the maximum charge on a cloud is of the order of 10 Coulombs, it is built up exponentially over a few minutes
- the maximum potential of a cloud lies in the range of 10MV to 100MV
- the energy in a lightning stroke is in the order of 250KWhr

The phenomenon of lightning is now generally accepted to be a means of keeping in balance the global electric system. This system consists mainly of the lower ionosphere (50 to 75 km above the ground) and the earth surface, forming a capacitor with the air between them acting as an imperfect di-electric. This is the global capacitor. Lightning is natures device to restore the potential difference of the global capacitor. Lightning causes a charge re-transfer to maintain a 300kV potential difference. Lightning phenomenon is the discharge of the cloud to the ground. Since the lower part of the cloud is negatively charged, the earth is positively charged compared to the cloud (by induction). After a gradient of 10kV/cm (approximately) is set up in the cloud, the surrounding air gets ionized. A streamer starts from the cloud towards the earth. The current in the streamer is in the order of 100A and the speed is 0.5 ft/micro second (0.15 m/micro second). The stepped leader is the branched streamer and it is a function of the degree of ionization of the surrounding air. The return power stroke moves upwards towards the cloud through the ionized path, when the leader reaches the ground. This return streamer carries 1KA to 200KA and reaches the cloud in 10% of the speed of light (30 m/micro second). Lightning flashovers can now be observed by the naked eyes. The dart leader (return) travelling at 3% of the speed of light, can take place to neutralize a close by
-ve charged cell in the cloud. It is found that each thunder cloud may contain as many as 40 charged cells and multiple strokes may occur. It is estimated that 700 to 800 active thunderstorms every instant have to take place to compensate for the leakage between the earths surface and the ionosphere.
Travelling Waves:

When the lumped sum parameters of circuits become inadequate for the transients analysis, the travelling wave approach is used. An analogy that can be used here to clarify this approach is a tank of water, referring to the voltage source, a pipe referring to the transmission line and finally the valve corresponding to the switch. When the valve is opened, at any instant, the pipe ahead of the wave of water is dry, while the one behind is filled with water to its capacity. For an electrical circuit, there is a gradual build up of voltage over the line, thus a voltage wave can be considered travelling from one end to the other and the charging of the distributed capacitance of the line is gradual, due to the associated current wave. The velocity of propagation of the wave is found to be the speed of light 300 m/sec. (984 ft/sec.). Another property of a transmission line or a cable is the surge impedance, which is independent of the load, ($(L/C)^{.5}$, where L is the inductance = $2\ (10^{-7})\ \ln(d/r)$ H/m and C = $2\ (\pi)\ (\varepsilon)/\ln(d/r)$ F/m; where ε is the permitivity of the medium (for vacuum, it is equal to $8.8\ (10^{-12})$ F/m), r is the radius of the conductor and d is the distance between conductors). The surge impedance for an overhead line is in the order of 400 ohm and for cable 30 to 40 ohm. As will be shown later, the surge impedance influences the degree of overvoltage, due to direct lightning strokes.

In general, protection to overhead lines is provided through shielding and or clamping. At the distribution level, only clamping (use of lightning arresters) is used. The use of shield wires is only used for transmission level lines. Direct strokes, induced and indirect strokes can affect distribution lines.

When a direct stroke hits a phase conductor, two waves will travell in opposite directions on the line, with voltage peak (V=1/2 ZI), where Z is the surge impedance of the line and I is the lightning stroke current in amps. The time taken to build up the voltage to the peak level is a function of the wave shape. It takes the wavefront time of the current stroke to reach the peak volt, this could be 4 micro seconds or 8 micro seconds.

Inadequate lightning protection results in through faults from the transformer substation, that will cause feeder tripping. When arresters are physically separated from the equipment to be protected, additional voltage comes on the equipment (induced voltage). The increased voltage rise is mainly due to lead inductance. The voltage rise/drop is equal to the inductance of the lead times the rate of rise of the stroke current. The shunt path through the arrester to ground includes the line lead to the arrester and the ground lead from the arrester to ground electrode, in addition to the impedance of the arrester.

The wave shape of the transient waves mostly used to calculate the overvoltage are 4/10 micro seconds and 8/20 micro seconds. With the same stroke current and wave shape as the latter, the distance between the arresters can be more than (about twice that of) the former wave.

The higher the surge impedance of the line, the closer the lightning arresters have to be. As more and more digital (microprocessor-based) relays are used in transformer stations, these relays can register the currents at which the breaker (feeder) trips. In a thunderstorm, if the reason for tripping is related to lightning, the registered S.C. level and the phase that flashed-over can give approximately the location of the weak point. A curve giving the distance from the station against the short circuit levels for single phase to ground, phase to phase to ground and three phase to ground can always help in identifying the area of the faults.

Reinforcing such location with additional lightning arresters spaced properly, can reduce the autos (tripping) and maybe lock-outs of feeder breakers. If the conclusion of the autos is that the induced strokes are the cause of the problem, raising the BIL level of each structure can help in alleviating this problem. Insulator and lightning arresters washing can help reduce the number of power interruptions. Insulators can also be cleaned by hand wipping. Overspray may cause flashovers. Contaminated insulators or L.A. may cause excessive leakage current to flow, causing pole fires or insulator flashover. The water minimum resistance to be used in washing is 1000 OHM/cubic cm. The hose nozzle is to be grounded to the neutral or ground conductor. The hose nozzle to be kept a safe distance from the energized conductors. The pressure of the water should be maintained high enough.

Types of lightning arresters:

Lightning arresters can be classified accordingly:

- distribution (heavy, normal and light duty)
- riser pole
- intermediate

Station type are used in substation rather in the overhead system. The standards that cover the performance/testing of arresters are the CSA 233, ANSI C62 and IEC 37. In general, the heavy duty arresters are used to protect O/H distribution systems exposed to severe lightning currents, normal duty to systems exposed to normal lightning currents and light duty to portions of the system where the severity of the stroke is discharged by an arrester (heavy, normal, intermediate or riser pole) located ahead of such sections. Riser pole or intermediate class arresters are used when lower discharge voltage (when the discharge current is flowing) is needed so not to stress the downstream equipment (expose them to a higher voltage). Examples for locations of L.A. are: dip/riser poles to protect underground distribution equipment and cables. The two designs that are available today are the non-linear resistor (silicon carbide plus spark gaps) and zinc oxide (with or without spark gaps). The non-linear resistor has the property that its resistance diminishes sharply with the voltage across it ($I=KV^n$), where n is between 2 and 6, I is the current through the resistor and V the voltage across it. The metal oxide resistor has an n between 20 and 50, K is proportional to the cross section area of the element and inversely proportional to its length. In this design of gaped SiC (silicon carbide) arresters, the non-uniform voltage distribution between the gaps may present a problem. Capacitors and non-linear resistors (thyrite) are connected across the gap and coil inside the arrester. The coil is used, basically, to utilize the follow power current and produce a magnetic force to push the arc or arcs in the gap unit or units into the arc quenching zone, to assist in de-ionizing the gap at first current zero. If this stage is not achieved, destruction to the arrester becomes inevitable. The metal oxide material is a crystalline one with 90% zinc oxide, the material ground, mixed and pressed to form the disk-shaped blocks with dense, fine structures. The volt/current ch/cs of metal oxide is a function of the boundary layers, the grain size and the composition. The gapless arrester must support the normal system voltage at all times. For a given voltage, the current increases with temperature. Thermal runaway would prevail when the MOV is operated continuously at a much higher than its maximum continuous operating voltage. For gapped arresters, the voltage distribution between the gap section and the MOV is determined by the capacitance across the gaps and the inherent capacitance of the MOV. At time of overvoltage, the gaps spark over. Then, the MOV gets into conduction and the maximum voltage experienced by the protected equipment is a function of the MOV discharge voltage. The characteristics of arresters are:

-the maximum continuous operating voltage (MCOV)

-duty cycle

-maximum energy capability

-maximum discharge current

-discharge voltage / currents relationship

The routine tests that are performed on all gapless arresters are:

- peak values of arrester currents (total and resistive) when the voltage applied to the arrester is equal to the MCOV (the rated voltage and a reference voltage at a stated ambient temperature)
-discharge voltage measurement at the rated discharge current
- RIV when the arrester is subjected to 1.1 MCOV
The design tests are:
-insulation withstand
-discharge voltage / current ch/cs
-surge current withstand
-line and rectangular wave discharge
-contamination
-internal RIV and pressure relief
The conformance tests include the routine tests plus thermal stability on an agreed upon quantity of arresters. One comment worthwhile mentioning here is that the level of voltage at which the intermediate arrestors are tested, is higher than distribution for impulse, 60 HZ RMS dry (1 min.) and wet (10 sec.).
The routine tests that are performed on gapped arresters (with integral series gaps) are the dry and wet power frequency sparkover tests.
The design tests are:
-voltage withstand
-power frequency sparkover
-impulse sparkover
-discharge voltage ch/cs
-discharge current withstand
-duty cycle test
-internal ionization
-pressure relief
-pollution
The conformance tests are the routine tests plus the impulse sparkover and discharge voltage to be performed on an agreed upon number of arresters.
Failure of an arrester can be attributed to any of the following:
-moisture leakage
-contamination
-overvoltages including switching and resonance
-surges of excessive magnitude and duration
Detecting of arrester failure in the field can be accomplished in any of the following ways:
Leakage Current
It is a good symptom of the condition of the arrester. High leakage currents indicate the internal deterioration of the arrester, this leads to an increase of the temperature of the arrester. A temperature rise of 10-20°C can be detected by infra-red thermography or infra-red thermometer remote sensing.
Insulation Resistance
Arresters with large leakage currents will demonstrate a lower insulation value when tested with a 2.5 kV megger. Thus, testing will indicate a defect or an arrester with deteriorated internal resistance.
Computer programs can give the flexibility of changing the conductor size/clearance, insulation levels, grounding and observing its impact on the lightning immunity of the system. These programs can

perform the travelling wave calculations for direct hit and induced voltages. From these calculations, for a given ground flash density, the feeder flashover per year can be given.
The number of direct hit flashovers can be found by multiplying the number of direct hits to the line by the percentage of flashovers (it is found by taking the flashover current and relating it to its probability of occurrence). The number of induced flashovers can be found by converting the critical distance and current curves to probability curves. The area between these curves, when multiplied by the ground flash density in flashes / km² and the length of the line in km, gives the total number of induced flashovers on the line. The output curves of such programs are:
- voltages due to a direct hit to the top phase, it gives the over-voltage level in kV vs. the time in micro seconds
- induced voltages for (indirect) strokes at X distance from the line, it gives the O/V vs. time
- the percentage of direct hits that cause flashovers for various arrester spacings, it gives the percentage flashover vs. spacing between arresters
- induced flashovers for various BILs (it is the relation between the induced flashovers, 100 km/year vs. the BIL level of the structure in kV, usually it ranges from 150 to 400 kV BIL).
Energy capability of an arrester:
This value is given in KJ/KV at the MCOV. It represents the capability of the arrester to withstand the line overvoltage. A curve for the arrester rating, surge impedance, length of line, as function of the line charge voltage in multiples of the peak line to ground voltage gives the capability of the arrester in dissipating (due to line switching) the energy. Discharge currents from the capacitor banks and cables can be higher than those from overhead systems. Thus the energy capability can be less than with the overhead lines.

I-3- Utilization:
After the power has been generated by steam or hydraulic turbines/generators, stepped-up through a step-up transformer, transmitted over towers/insulators/transmission lines, distributed in terminal stations using air or gas insulated systems (bus and breakers), reaching transformer stations where step-down transformers are used to step down the voltage from transmission to subtransmission/distribution levels, the power passes through medium voltage overhead conductors or underground cables to the distribution transformers that further step-down the voltage to the utilization level (600v or less). The loads and their characteristics found in industrial plants or commercial institutes or residential subdivisions varies dramatically. The requirements of the different types of loads when it comes to power availability vs quality vary widely. 75% of industrial loads are squirrel cage induction motors, the rest are lighting, heating, computer systems and welding machines (if any).
I-3-1 Squirrel cage induction motors (SCIM): The power is supplied to the motor through the starter and if speed control is required, then a variable speed drive is connected between the source and the motor terminals. Induction motors have to be modelled for 4 conditions normal operation, starting, during faults and for transients analysis. In induction motors, a.c. is supplied to the stator winding directly and to the rotor winding by induction from the stator. The mmf waves created from the stator and rotor currents are stationary with respect to each other as they are rotating at synchronous speed in the air gap. The mmf waves will have constant amplitudes and their resultant creates the air gap flux density wave. At all speeds (other than the synchronous), the torque produced is steady. The torque angle of an induction motor is equal to 90 degrees plus the rotor power factor. The following equation expresses the relation between the rotor induced emf, induced current and rotor impedance referred to the stator: $E_{2s}/I_{2s} = Z_{2s} = r_2 + jsX_2$, where E_{2s} is the slip frequency emf generated in the rotor phase and

referred to the stator, I_{2s} is the current in the rotor phase, Z_{2s} is the slip frequency rotor leakage impedance per phase referred to the stator r_2 is the referred effective resistance and sX_2 is the referred leakage reactance at slip frequency. For the stator: $V_1 = E_1 + I_1 (r_1 + jX_1)$; where V_1 is the stator terminal voltage, E_1 is the counter emf generated by the resultant air gap flux, I_1 is the stator current, r_1 is the effective stator resistance and X_1 is the stator leakage reactance. The stator sees a flux and an mmf wave rotating at synchronous speed. The flux wave induces the slip frequency rotor voltage E_{2s} and the stator counter emf E_1. The flux wave speed with respect to the rotor is s times its speed with respect to the stator ($f_2 = sf_1$). The rotor mmf wave is opposed by the mmf of the load component (I_2) of the stator current. $(E_{2s}/I_{2s}) = sE_1/E_2$, thus $E_1/I_2 = r_2/s + jX_2$.
Now, the equivalent circuit is complete for the steady state analysis. For the equivalent circuit of a 3-phase induction motor, click here. For starting and short circuit contribution of induction motors, the equivalent circuit is reduced to a leakage reactance X' and a resistance r in series.
For short circuit motor contribution, the following procedure may be applied: $X' = X_1 + [(X_\phi X_2)/(X_\phi + X_2)]$; where X_1 is the stator leakage reactance, X_2 is the rotor leakage reactance, X_ϕ is the magnetizing reactance.
$I_1 = E_1'/X'$; where I_1 is the initial rms short circuit current contributed from the motor, E' is the prefault voltage (behind the transient reactance X').
$T_o' = X_2 + X_\phi/2\pi f r_2$; where T_o' is the open circuit transient time constant, r_2 is the rotor resistance.
$T' = T_o' [(X')/(X_1 + X_\phi)]$ in seconds; where T' is the short circuit transient time constant $I1 = (E'/X') e^{-t/T}$ amp.
For starting motor analysis the following procedure may be used:
$V_1 = I_1Z_1+\{(I_1)/[(1/Z_2')+Y_m]\} = I_1 K$; where V_1 is the stator terminal voltage for 1 phase (of the 3 balanced phases), I_1 is the primary current per phase, Z_1 is the primary (stator) impedance $= r_1+jX_1$, Z_2' is the rotor impedance referred to the stator $= r_2' + r_2' [1-s/s] + jx_2'$ and Y_m is the main flux admittance $= g_m - jb_m$ (i.e. $r_m = g_m/(g_m^2+b_m^2)$, $X_m = b_m/(g_m^2+b_m^2)$ & $Z_m = r_m + jX_m$). The motor parameters: r_1, X_1, r_2',X_2', r_m and X_m (or g_m and b_m) are determined from the no load and the locked rotor tests. From the no load tests the following data are obtained: the stator terminal voltage (V_1), the no load stator current (I_o) and the power consumed (P_o), from which the main flux admittance-related parameters are calculated. From the locked rotor (full voltage) test, the following data are obtained: the stator voltage the stator current (under locked rotor condition) and the power consumed, from which r_1, r_2' and the saturated reactance are calculated. From the locked rotor test with reduced applied voltage, the following data are obtained: the stator voltage and current, from which the unsaturated impedance and stator plus rotor reactances are calculated. The parameters r_2' and X_2' (unsaturated) have to include for the skin effect (by multiplying or dividing each value by an appropriate factor). The performance of the induction motors is related to its parameters and is defined by the following factors: the full load torque slip) at the full load torque), the total active power loss in the rotor circuit, the output HP at the full load torque, the slip at pull out (maximum) torque, the rotor current at maximum torque, the

starting torque and the starting current. The torque of a polyphase induction motor can be given by: $T=(7.04)\ (P_{watts})/n$ in LB-ft$=7.04\ (P_{rot})/n_s$ LB-ft, where P_{rot} is the power transferred by the rotating field, n_s is the synchronous speed, $P_{rot} = 3Io'^2\ r_2'/s$ in watts. At stand-still, the rotor frequency equals the stator frequency, as the motor accelerates, the rotor frequency decreases to a very low value (2 or 3HZ). By use of suitable shapes and arrangements, the rotor bars (squirrel cage) can have effective resistance at 60HZ which are several times that at 2 or 3 HZ. These rotor slots arrangements are the deep bar rotor and the double cage (Boucherot) rotor. At the higher frequency (i.e. 60HZ), the rotor current flows only in a part of the cross section of the rotor conductor and the rotor resistance appears high. At the rated load and when the frequency is 2 or 3 HZ, the whole cross section of the rotor conductor is effective and r2 is small. The characteristics of the different 3 phase SCIM are best described by the NEMA designations: class A (normal starting torque, normal starting current and low slip), class B (normal starting torque, low starting, current low slip), class C (high starting torque, low starting current) and class D (high starting torque, high slip). Larger motors that may cause high voltage drops on the system during starting at full voltage (direct across the line) can be started at reduced voltage. In this case, the starting current will be lower though at the expense of the starting torque which will be lower also by a factor equal to the squared voltage applied during starting compared to direct across the line voltage magnitude. The methods used to have a reduced starting voltages are: auto-transformers, Y-Δ transformation of stator windings and resistance starting. To have a variable speed motor any of the following principles may be used: changing the number of poles in the motor, varying the line frequency supplied to the stator terminals, varying the line voltage magnitude, varying the rotor resistance and the application of the appropriate voltage of the right frequency to the rotor circuit (if wound rotor motors are used). When motors are starting, there will be an imrush current flowing which can be anything from 4 to 10 times the full load current. The calculation procedure for the starting current magnitude was given previously, the duration can be taken as 10 seconds or calculated if the speed (slip) - torque characteristics curves of the motor and load are known. The time required to attain a speed $\omega o = J \int_{o}^{wo} (1/\Delta t)(d\omega o)$; where ω o in mechanical radians per sec., J is the rotor + load inertia in MKS, Δ t is the differential torque between that produced by the motor and that required to turn the load (available to accelerate the mass). A simplified approximation for starting time is given as follows:

$t(s) = WK^2\ (rpm_1 - rpm_2)\ 2\pi/(60\ T_n\ g)$; where $g = 32.2$ ft/sec², T_n is the net average accelerating torque between rpm_1 and rpm_2, WK^2 is the total inertia constant in LB ft² and t is the time to accelerate in sec. Before covering briefly, single phase induction motors, lets differentiate between rotating mmf (flux) and alternating flux. The former having a constant magnitude and rotating (travelling) in space, (in the gap) the latter having a variable magnitude and in fixed in space. The alternating mmf can be replaced by two rotating mmfs travelling in opposite directions and each having an amplitude equal to half of that of the alternating mmf. Any 3-phase induction motor can be made to operate as a single phase induction motor by opening one of the 3 stator phases. The two remaining stator phases constitute a single phase winding distributed over 2/3 of the pole pitch. Contrary to the polyphase induction motor, where the rotor emf is induced by only one rotating flux, it is induced in single phase motors by 2 rotating fluxes. The two rotating fluxes have an opposite influence upon the rotor (one to motor it and the other to brake if). The developed torque due to the forward rotating flux $= 7.04\ (I_{2f}'^2\ r_2')/s(n_s)$ LB-ft., that due to the backward one = 17.04 $(I_{2b}'^2 r_2')/n_{s<}(2-s)$. The resultant developed torque = $T_f + T_b$; where I_{2f}' and I_{2b}' are the currents produced in the rotor by the forward and backward fluxes, respectively. At stand still, s=1 and 2-s=1, thus the rotating starting torque =0. Regardless of the direction of rotation, a driving torque will be present as soon as the rotor starts to rotate. The equivalent circuit of the single phase induction motor can be produced using Kirchoff's mesh equations of the stator and the 2 rotor circuits (the 2 emfs, currents and frequencies sf_1 and $(2-s)f_1$ induced in the rotor).

To start a single phase motor, either a rotating flux (such that in the polyphase motor) has to be produced or the addition of a commutator with brushes to the rotor is necessary. The first type of starting will achieve a time phase shift between the currents in the main and starting windings through the following designs: split-phase motor, resistance start split phase motor, reactor start split phase motor, capacitor start motor, permanent split capacitor motor. The last type of starting will include the following designs: repulsion start induction motor, repulsion induction motor. For very small output and a small starting torque, shaded pole motor design is used. The parameters of the single phase induction motors (r_1, X_1, r_m, X_m, r_2'/s, X_2', $r_2'/(2-s)$ can be determined by performing the no-load and locked rotor tests on the motors. The no load test is run at rated voltage V_1 with the starting circuit open. I_o (no load current) and P_o (no load power input) are measured. The power input at no load will include the iron losses due to the main flux, friction and windage losses, the rotational iron losses, the copper losses in the stator windings and the copper losses in the rotor windings (can be assumed to be equal to those in the stator). The following parameters are determined from the test: the main flux reactance and resistance, provided that the stator parameters (r_1 and X_1) and the rotor parameters (r_2' and X_2') are known. The stator and rotor parameters are calculated from the locked rotor tests. This is run with the starting winding open. The following data are measured: the short circuit (locked rotor) stator voltage, current and power consumed. For the equivalent circuit of a single phase induction motor, click here.

I-3-2 Lighting: There are different applications for lighting eg. utility street lighting, residential, industrial, ..etc. There are different fixtures designs and lamps with different power ratings that provide for such needs. The lighting fixtures may be fed from dedicated transformers or others that are used to distribute power to other types of loads like houses, motors, etc. Light is an electromagnetic radiation like radio waves, but of a much smaller wave length. The relation between the wave length and the frequency is $f\lambda = 3\,(10^8)$ m/sec. For example if $\lambda = 6\times10^{-5}$ cm, $f = 5\times10^{14}$, which is an orange yellow colour; $\lambda = 3\times10^4$ cm, then $f = 10^6$ c/s this is a medium length wireless wave. Luminous flux is defined as the rate of passage of radiant energy evaluated according to the luminous sensation produced by it, the unit of luminous flux is the lumens (it is the luminous flux emitted in a unit solid angle-steradian by a source of 1 candle power). The luminous intensity in any given direction is the luminous flux per unit solid angle emitted in that direction. Note that the visual sensation depends upon the wave length as well as the rate of emission of energy. If the wave length of optimum sensitivity is considered, an expression of the luminous flux (in lumens) can be expressed in terms of the rate of emission of radiant energy (in watts). The mechanical equivalent of light is given as 1 lumen = .0015 W (at 5500 Å:angestrom). The illumination at a point of a surface is defined as the luminous flux per unit area at the point, expressed in lumens/square meter or square foot (1 lumen/m² = 1 lux, 1 lumen/ft²=1 foot-candle). The inverse square law, which is used widely in the calculations of illumination, states that if the luminous intensity in a given direction of a diverging source is I lumens/steradian, the illumination at a point distance r from the source is I/r^2 lux if r in m (in f.c. if r is in ft). The brightness of a surface is defined as the luminous intensity per unit projected area of the surface i.e. the candles per unit area, as viewed. Under certain conditions, the brightness may depend upon the angle of viewing. When light strikes a surface, a portion is reflected and the rest is absorbed. The coefficient of reflection is the ratio of the luminous flux leaving the surface to the flux incident on the surface (white paper reflects 80%, common white paper and wood reflects 40%, a white ceiling reflects from 40 to 70%). When light passes through a transparent material, some is absorbed; the ratio of the light absorbed to the light entering is called the coefficient of absorption. When it is required to calculate the illumination provided by a given set of lamps and reflectors (or shades), the polar curves of the sources and fittings, the use of the inverse square and Lambart's cosine laws can provide a simple solution. The polar curves show the candle power vs. direction. The cosine law states that an inclined surface will have an illumination which is cos q times that on the normal surface to the axis of the light (cone), where q is the angle between the normal to the surface and the light axis. The most commonly used sources of light are: incandescent filament lamp (carbon or tungsten coil) and gas discharge electric lamps (sodium or mercury vapour). Glare is the light that reflects (brilliantly) from a shiny surface. Otherhttp://www.geocities.com/haakheir/cpfig23.gif types of annoying lights are the stray light. Contrast is a factor that is considered (is simply the degree of difference between light and dark areas) during the design stage. General guidelines exist that give the levels of illumination (in fc. or lux) for the different activities done in the different areas of an institution, a plant, a commercial building, etc. For example, concentrated tasks may require from 100-125 foot candles, less concentrated tasks require 50-75 f.c., familiar tasks: 25-50 f.c., low level activity 10-25 f.c. and general basic mobility, 2-10 f.c. The required illumination can be calculated in terms of lumens by multiplying the required foot candle, for the areas required to be illuminated, by its area. It may be mentioned here that a full sunlight at noon time provides 10,000 f.c. and a cloudy sky about 500 f.c. Dividing the number of lumens required by the number of lumens per watt provided by the source of light used will provide the watts required to illuminate the area (to be illuminated). The distribution of light in street lighting is most important, in order that the power used may not be excessive and the lighting be best for the physical area to be illuminated. In order to avoid glare, the ratio of the maximum intensity to that in the downward vertical direction should not exceed 6 (approximately). Also, the maximum intensity in candles should not exceed ½ the numerical value of the flux emitted by the bare lamps in lumens. To prevent apparent shadows near the post, the distribution between the downward vertical and the maximum directions should give a flat bottomed polar curve. To give long, wide, bright areas and to avoid waste of lumens, the region of maximum intensity should extend from about 77.5 to 87.5 deg. from the vertical axis; above which the intensity should diminish as rapidly as possible.

I-4 Basic operations and basic values calculations:

I-4-1 Equivalent of parallel circuits: the equivalent of a few parallel branches of resistances is calculated accordingly: $1/R_{eq} = 1/R_1 + 1/R_2 + 1/R_3 + ... 1/R_n$; where R_1, R_2 are the resistances of the branches in ohm. If the branches are reactances, the same approach is used i.e. $1/X_{eq} = 1/X_1 + 1/X_2 + 1/X_3 + ... 1/X_n = K$ and $X_{eq} = j/K$

For impedance: $1/Z_{eq} = 1/Z\angle\theta + ... 1/Z\angle\theta = |K|$ $Z_{eq} = 1/K\angle\theta_{eq}$

I-4-2 Equivalent of series branches: the equivalent of a few series elements of resistances, reactances or impedances is given accordingly.

$R_{eq} = R_1+R_2+...R_n$
$X_{eq} = j(X_1+X_2+...X_n)$
$Z_{eq} = (R_1+R_2+R_3...) + j\ (X_1+X_2+...X_n)$

I-4-3 Delta - wye and vice versa transformations: this type of transformation is done when simplifying a circuit representing a distribution system, during the process of fault calculations, has to be performed. This circuit can be the positive sequence network of reactances, negative sequence or zero sequence network. This transformation may also be performed in steady state stability analysis to calculate the transfer impedance between 2 buses. For a sketch of wye-delta connection, click here.
To transform from delta to wye:
$Z_{1n} = (Z_{12})\ (Z_{13})/(Z_{12}+Z_{23}+Z_{13})$
$Z_{2n} = (Z_{12})\ (Z_{23})/(Z_{12}+Z_{23}+Z_{13})$
$Z_{3n} = (Z_{23})\ (Z_{13})/(Z_{12}+Z_{23}+Z_{13})$
To transfer from wye to delta, the following equations can be used:
$Z_{12} = [(Z_{1n})(Z_{2n})/Z_{3n}]+Z_{1n}+Z_{2n}$
$Z_{23} = [(Z_{2n})(Z_{3n})/Z_{1n}]+Z_{2n}+Z_{3n}$
$Z_{13} = [(Z_{1n})(Z_{3n})/Z_{2n}]+Z_{1n}+Z_{3n}$
Where Z_{12}, Z_{23} and Z_{13} are the elements of the DELTA circuit between the 3 buses 1,2,3; Z_{1n}, Z_{2n} and Z_{3n} are the elements of the WYE equivalent.

I-4-4 Fault currents calculation for simple grounded system: Fault currents in power systems can be calculated using either the traditional method of circuit reduction or the impedance network model. Further discussion of faults in power systems will be provided later in Chapter 3 “Faults in power systems”. Here, a discussion of solidly (neutral) grounding with and without fault resistance will be presented. Grounding types of systems and the different neutral configurations will be given later in Chapter 3. Using the circuit reduction method for a simple solidly grounded neutral system, and to calculate the fault currents follow the following procedure:
-From the single line of the system construct the reactance diagram for the positive, negative and zero sequence networks. Starting from the source all the way through all the buses in the system show reactances connecting any two buses in the network including transformers, line conductors, cables, capacitors and motors (if available). The positive sequence network will have a voltage source at the starting point. The negative sequencenetwork will have in place of the +ve sequences reactance, the -ve sequence reactance values with the source shorted. The same is applicable for the zero sequence network. The faulty bus and the reference node (bus), which is the neutral in this case, will act as the main buses at which the reduced circuit (equivalent reactance) will be calculated. This process is applicable to the +ve, -ve and zero sequence networks, the connection of the different networks to each other is function of the type of fault being investigated. The different types of parallel faults (series faults will be covered in Chapter 3) are single line to ground (70% of all faults), line for line (15%), line to line to ground (10%) and 3-phase (to ground or not) represents 5% of all faults. In order to obtain the reactances in final stage to be included in the calculation, the reactances has first to be in ohms or in percent, after selecting the base values of voltage and MVA, the impedance base is calculated. Dividing the ohm reactance by the base will lead to the p.u. value that can be placed on the reactance diagram and used in the reduction process (more about base value selection and per unit calculation will be

provided later in this chapter in Section 4.9). If the percent impedance value is based on the machine rating, it has to be converted using the base values before being used in the calculations. The sources that would contribute to a fault are the generators (or through the power transformers or distribution transformers), synchronous motors, S.C.I.M. and capacitors (with the capacitors the contribution is for a very short duration with an irregular shape of fault current wave). As the current will always flow through the lowest resistance available path, under fault conditions only the faulty branch plus the other secondary contributing branches are used in the calculations. For the calculation of the motor contribution to a fault and the duration of each contribution, refer to Section 3.1 of this chapter). For the different interconnections of the impedance sequence networks of the different types of faults, click here.

• For single line to ground faults, the prefault voltage at the faulty bus in p.u. has to be known (assumed 1 p.u.) and the sequence networks are connected in series:

$I_o = I_1 = I_2 = I_{fault} / 3$ = Prefault voltage / $(Z_1 + Z_2 + Z_3)$; assuming a fault resistance = 0

$I_o = I_1 = I_{2p.f.}/(Z_1+Z_2+Z_0+3Z_f)$; where Z_f is the fault resistance.

• For line to line faults: $I_b = -I_c$ assuming phase b touches phase C, the sequence networks - positive and negative - are connected in series with the exciting voltage equal the prefault voltage, $I_{a1} = I_{a2}$ as $I_{ao} =$ 0. $I_{a1} = V_{pf} / (Z_1+Z_{2b=Ib1+Ib2+Ibo}$, Ib= a² Ia1+ a Ia2; where a = 1 $\angle$ 120° = -.5 + j.866, a² = -.5 -j .866, Ib is the fault current. Symmetrical components were used above, full coverage will be presented in Chapter 3. For a fault with resistance Ia1 = Vpf / (Z1+Z2+Zf).

• For line to line to ground faults, the 3 sequence networks have to be connected together and their values will be used in the fault current calculations. If the fault is between phases b and c plus ground, then the fault current = Ib + Ic. The zero sequence network is connected in parallel with the negative sequence network and this combination is connected in series with the positive sequence network and the prefault voltage.

Ia1 = Vpf/[Z1+(Z2Zo/(Z2+Z0))]

Va1 = Vpf - Ia1 Z1; Va1 = Va2 = Vao; -Ia1-Ia2 = Iao

Iao = -Vao/Zo; fault current = a²Ia1 + aIa2 + Iao + a²Ia2 + aIa1 + Iao = - Ia1 - Ia2 + 2 Iao

For a fault with resistance in the fault path, Ia1=Vpf/[Z1+(Z2(Z0+3Zf)/(Z2+Zo+3Zf))]

• For 3 phase fault, the fault is symmetrical thus only the positive sequence network is used and the fault current = Vpf/Z1.

I-4-5 Matrix manipulations for 2x2 and 3x3 matrices: The operation performed on matrices (which are built from simultaneous equations representing a power system modeled for certain study) are the determinant value calculation and the inversion of the matrices.

These operations are commonly required when running load flow studies.

- For a 2 by 2 Matrix:

If $A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$ $A^T = \begin{bmatrix} a_{11} & a_{21} \\ a_{12} & a_{22} \end{bmatrix}$

where A^T is the transpose of A matrix, i.e. columns become the rows and the rows become the columns.

d = determinant = (a11) (a22) - (a12) (a21)

$$A^{-1} = \begin{bmatrix} a_{22}/d & -a_{12}/d \\ -a_{21}/d & a_{11}/d \end{bmatrix}$$

;where A^{-1} is the inverse of matrix A and is formed accordingly from A^T and d the first element of $A^{-1} = (-1)^{m+n}$ a22/d; where m is the row number (in this case = 1) and n is the column number (in this case = 1) and so on for the other elements.

- For a 3 by 3 Matrix:

$$\text{If } A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}; \quad A^T = \begin{bmatrix} a_{11} & a_{21} & a_{31} \\ a_{12} & a_{22} & a_{32} \\ a_{13} & a_{23} & a_{33} \end{bmatrix}$$

d= a11[(a22) (a33) - (a32) (a23)] -a12[(a21) (a33) - (a23) (a31)] +a13[(a21) (a32) - (a22) (a31)]

$$A^{-1} = 1/d \begin{bmatrix} -(a_{22})(a_{33})-(a_{23})(a_{32}) & -[(a_{12})(a_{33})-(a_{13})(a_{32})] & (a_{12})(a_{23})-(a_{13})(a_{22}) \\ -[(a_{21})(a_{33})-(a_{31})(a_{23})] & (a_{11})(a_{33})-(a_{13})(a_{31}) & -[(a_{11})(a_{23})-(a_{13})(a_{21})] \\ (a_{21})(a_{32})-(a_{31})(a_{22}) & -[(a_{11})(a_{32})-(a_{12})(a_{31})] & -(a_{11})(a_{22})-(a_{21})(a_{12}) \end{bmatrix}$$

The same approach as that used for the 2x2 matrix, to get each element of the inversed matrix, the row and the column of the element sought are eliminated and the determinant of the left (2 columns x 2 rows) is calculated and multiplied by $(-1)^{m+n}$ and then divided by d.

I-4-6 Simultaneous equations solution using gausssian elimination and triangular factorization: this method of simultaneous equations solution is mostly used (in power systems analysis) to solve load flow studies when the number of buses exceed 3 (excluding the slack bus). More coverage of load flow studies will be presented, later, in Chapter 4. The detailed procedure will be given hereafter for 4 equations. This procedure can be applied for 5,6,7...simultaneous equations when the number of buses (excluding the slack) are 5,6,7...

Y11 V1 +Y12 V2 + Y13 V3 + Y14 V4 = I1
Y21 V1 +Y22 V2 + Y23 V3 + Y24 V4 = I2
Y31 V1 +Y32 V2 + Y33 V3 + Y34 V4 = I3
Y41 V1 +Y42 V2 + Y43 V3 + Y44 V4 = I4

The above are the nodal admittance equations of a four bus system (more will be said about admittance equations later in this chapter under Section 4-8) in V1, V2, V3 and V4 which are unknown. The method of gaussian elimination (successive elimination) means reducing the system with 4 unknowns to a three equation system with 3 unknowns then to 2 and finally to one equation in 1 unknown. The unknown is now known and then can be backward substituted to yield V3, V2 and finally V1. This method can be combined with the triangular factorization method, as in this case it best suits the application of the combined method to load flow studies. To show how the combined method work lets write the equations in a matrix form.

$$\begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix}$$

[Y] [V] = [I]
Y is 4 by 4 matrix
V & I are 4 x 1 matrices

The Y matrix can be a B matrix (susceptance matrix), the digits shown between the brackets are the number of rows by the number of columns of the matrix.

L (4 x 4) . U (4 x 1) . V (4 x 1) = I (4 x 1) and U.V = V'

Step 1 in the elimination process: Y110 = Y11/Y11 = 1

Y120 = Y12/Y11, Y130 = Y13/Y11, Y140 = Y14/Y11.

Y220 = Y22-[Y21 (Y12)/Y11], Y230 = Y23-[(Y21)(Y13)/Y11], Y240 = Y24-[(Y21)(Y14)/Y11]

Y320 = Y32-[Y31 (Y12)/Y11], Y330 = Y33-[(Y31)(Y13)/Y11]

Y340 = Y34-[Y31 (Y14)/Y11], Y420 = Y42-[(Y41)(Y12)/Y11]

Y430 = Y43-[Y41 (Y13)/Y11], Y440 = Y44-[(Y41)(Y14)/Y11].

Step 2:

Y221 = Y220/Y220 = 1, Y231 = Y230/Y220

Y241 = Y240/Y220, Y331 = Y330 - [Y320(Y230)/Y220]

Y341 = Y340 - [Y320(Y240)/Y220], Y431 = Y430 - [Y420 (Y230)/Y220]

Y441 = Y440 - [Y420(Y240)/Y220].

Step 3:

Y332 = Y331/Y331 = 1, Y342 = Y341/Y331, Y442 = Y441 - [Y341 (Y431)/Y331]

The lower matrix (L) of the triangular factorization which is the same when the columns in successive approximation are eliminated in the forward stage. The upper matrix (U) elements are the same as those row entries successively generated of the forward stage of the gaussian elimination.

$$L = \begin{bmatrix} Y_{11} & & & \\ Y_{21} & Y_{220} & & \\ Y_{31} & Y_{320} & Y_{331} & \\ Y_{41} & Y_{420} & Y_{431} & Y_{442} \end{bmatrix}$$

$$U = \begin{bmatrix} Y_{110} & Y_{120} & Y_{130} & Y_{140} \\ & Y_{221} & Y_{231} & Y_{241} \\ & & Y_{332} & Y_{342} \\ & & & Y_{443} \end{bmatrix}$$

$$Y_{110} = Y_{221} = Y_{332} = Y_{443} = 1$$

The programs given later in this chapter will show this procedure written in quickbasic and C++ for more than 4 equations.

I-4-7 Impedance network models: building the impedance network model for a power system will assist in calculating the fault studies including voltage sensitivity (the voltage on the buses upstream the faulty one at time of fault). The coverage here will cover only the representation of branches with no mutual coupling and will cover networks and radial systems (with or without the effect of S.C.I.M. contribution). The 4 conditions that may exist in a system are: the presentation of an impedance connecting between the reference node (bus) which can be the neutral or ground of a system and a new bus, the connection between an old bus and a new one, the connection between an old bus and the reference node and finally the connection between 2 old buses. For mutually coupled elements, refer to reference no.[3] given in the list at the end of this Chapter. Lets assume a network with reference node 0, then equipment and lines go out radially from the reference node or bus 0 (which is the neutral, the 3 phases are assumed to be balanced and a single phase out of the 3 phases is represented here) to bus 1, bus 1 is connected to bus 2, bus 2 to 3 and, finally, 1 to 3. For a typical sketch of an impedance (reactance) diagram, click here.

Step 1: Zbus = [Z01]; bus 0 to 1

$$\text{Step 2: } Z = \begin{bmatrix} Z_{01} & Z_{01} \\ Z_{01} & Z_{01}+Z_{12} \end{bmatrix} \qquad \text{bus 1 to bus 2}$$

$$\text{Step 3: } Z = \begin{bmatrix} Z_{01} & Z_{01} & Z_{01} \\ Z_{01} & Z_{01}+Z_{12} & Z_{01}+Z_{12} \\ Z_{01} & Z_{01}+Z_{12} & Z_{01}+Z_{12}+Z_{23} \end{bmatrix} \qquad \text{bus 2 to bus 3}$$

$$\text{Step 4: } Z = \begin{bmatrix} Z_{01} & Z_{01} & Z_{01} & Z_{01}-Z_{01} \\ Z_{01} & Z_{01}+Z_{12} & Z_{01}+Z_{12}+Z_{23} & Z_{01}-Z_{01}-Z_{12}-Z_{23} \\ Z_{01} & Z_{01}-Z_{01}-Z_{12} & Z_{01}-Z_{01}-Z_{12}-Z_{23} & Z_{44} \end{bmatrix} \qquad \text{bus 1 to bus 3}$$

Z44 = Z01+Z01+Z12+Z23 - 2 [Z01] + Z13

Step 4a:the elimination of column and row 4 using Kron reduction method. The final Zbus matrix will have the following elements:

$$\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \quad \text{; where}$$

Z11 = Z01 - [(Z01-Z01)(Z01-Z01)/Z44]

Z12 = Z01 - [(Z01-Z01)(Z01-Z01-Z12)/Z44]

Z13 = Z01 - [(Z01-Z01)(Z01-Z01-Z12-Z23)/Z44]

Z21 = Z01 - [(Z01-Z01-Z12) (Z01-Z01)/Z44]

Z22 = Z01 + Z12 - [(Z01-Z01-Z12)(Z01-Z01-Z12)/Z44]

Z23 = Z01 + Z12 - [(Z01-Z01-Z12) (Z01-Z01-Z12-Z23)/Z44]

Z31 = Z01 - [(Z01-Z01) (Z01-Z01-Z12-Z23)/Z44]

Z32 = Z01 +Z12 - [(Z01-Z01-Z12) (Z01-Z01-Z12-Z23)/Z44]

Z33 = Z01+Z12+Z23 -[(Z01-Z01-Z12-Z23)²/Z44]

The last possibility would be the presence of an equipment (a generator or an inductionmotor that its effect has to be taken while calculating fault currents) between bus 3 - for example - and node 0 (reference). The step 4 above is replaced by the following step, and then Step 4 will be performed on the resultant matrix and it will become Step 5.

Step 4: from Step 3 above obtain the following matrix:

$$Z_{bus}=\begin{bmatrix} Z_{01} & Z_{01} & Z_{01} & Z_{01} \\ Z_{01} & Z_{01}+Z_{12} & Z_{01}+Z_{12} & Z_{01}+Z_{12} \\ Z_{01} & Z_{01}+Z_{12} & Z_{01}+Z_{12}+Z_{23} & Z_{01}+Z_{12}+Z_{13} \\ Z_{01} & Z_{01}+Z_{12} & Z_{01}+Z_{12}+Z_{23} & Z_{44} \end{bmatrix}$$

Z44 = Z01+Z12+Z23+Z03.

Step 4a: the elimination of column and row 4 using Kron elimination method mentioned above under 4a. Then Step 5 will become the addition of the impedance between buses 3 and 1 and this will add columns 4 and row 4 which are then eliminated (using Kron method) to yield the final network impedance matrix with the final impedance elements that can be used in fault studies. The latter will be shown in Chapter 3, Faults in power systems.

I-4-8Admittance network model: this model is used mostly in load flow calculations and consequently stability studies. The admittance matrix for non-mutually coupled is built accordingly for any power system: the diagonal elements of the (squared) matrix will equal the addition of all the elements connected to the subject bus (or node) i.e. lets assume the nth bus is taken, then Ynn=Y1n+Y2n+Y3n..., the off diagonal element will be the negative value of the element connecting the bus ahead with the subject bus as well as the bus downstream i.e. Yn-1 to n = -Yn-1 to n, Yn+1 to n = -Yn+1 to n. Thus, for a 4 bus simple radial system the

$$Y_{bus}=\begin{bmatrix} Y_{12} & -Y_{12} & 0 & 0 \\ -Y_{12} & Y_{12}+Y_{23} & -Y_{23} & 0 \\ 0 & -Y_{23} & Y_{23}+Y_{34} & -Y_{34} \\ 0 & 0 & -Y_{34} & +Y_{34} \end{bmatrix}$$

I-4-9 Base values and per unit calculations: The two base values that have to be selected for a power system are the megavolt ampere (MVA) and the kilovolt (KV). The former, once selected will stay the same i.e. 100 MVAbase selected at any point in the system will be maintained all over the system. The latter quantity has to be selected at the generating or main transformer (one at an extreme end in the network) and at each voltage transformation point (i.e. a transformer) it has to be multiplied by the ratio of the secondary to the primary voltage, the impedance (or reactance) base value = KVb²/MVAb at the point of calculation. There are a few important equations to transform the p.u. (if it is given at any other values than those of the base) to the base values selected. Vp.u. = Vactual in KV/KVb, Ib=MVAb x 1000/KVb,
Zpu = Z in Ω/Zb, Xpu= X in Ω/Zb, for motors or transformers Xp.u. = p.u. reactance x MVAb/motor or Xfo rating in MVA. For an example (radial) system showing the buses (nodes) plus the loads and transformers configurations where the P.U. system can be used to perform the power systems analysis and studies, click here.

Complete example programs in Quickbasic and C++

Contents

CHAPTER 3
FAULTS IN POWER SYSTEMS

I. Power Section:

Faults in power systems are imminent. Their causes, types and calculations will be given later, through this chapter. When faults occur in a system abnormal currents flow from the source through the lowest resistance path, passing by all the components between the sources and the faults. If the fault causes higher currents to flow, this will cause mechanical and thermal stressing of the components in the faulty path. If the fault will cause only an increase in the negative sequence current, this will be detrimental to induction motors. There are elements in the power system to sense fault currents (whether positive, negative, zero or composite sequence) and to isolate the faulty portion from the rest of the system. Thus the purpose of fault studies is to know the current flowing under different fault types, its magnitude and duration, so that the sensing and fault breaking devices can be selected accordingly. Also, the bracing of cables, conductors and poles of switches is also based on such studies. When a three phase unbalanced circuit (because of a fault or due to loading of power distribution systems) exists, using symmetrical components make it possible to calculate the positive sequence currents, negative sequence currents and zero sequence currents. It is worth mentioning here that the positive sequence current flows only in the positive sequence impedance of the network and produce a positive sequence voltage drop, the negative sequence current flows in the negative sequence impedance and produce a negative sequence voltage drop across it and the same for the zero sequence current (that flows in the zero sequence impedance of the network including the ground return path and the neutral impedance, if any). An unbalanced quantity (current or voltage) in three phase systems means that either the magnitude of all phases are not equal or the angle between the phases is not equal to 120 or both. The positive sequence quantity will have equal magnitude in all phases and shifted by 120° from each other in counter clockwise direction ie. A-120°-B-120°-C. For the negative sequence quantity, it will be equal in all phases and also separated from each other by 120° (though rotating in clockwise direction) ie. A-120-C-120-B. For the zero sequence, the quantities in all phases are equal with angle = 0 between the phases ie. A-0-B-0-C i.e. they coincide.

If V_A, V_B and V_C are the voltages (to neutral) on the 3 phases, then the positive, negative and zero sequence voltages will be as follows:

$V_{A1} = 1/3\ (V_A + a\ V_B + a^2\ V_C)$; $V_{A2} = 1/3\ (V_A + a^2\ V_B + a\ V_C)$

$V_{A0} = 1/3\ (V_A+V_B+V_C)$, the same is applicable for the 3 sequence currents in term of phase currents IA, IB and IC. Lets assume that the sequence quantities are known, then the phase values can be calculated accordingly:

$V_A = V_{A1}+V_{A2}+V_{A0} = V_{A1}+V_{A2}+V_{A0}$

$V_B = V_{B1}+V_{B2}+V_{B0} = a^2\ V_{A1}+a\ V_{A2}+V_{A0}$

$V_C = V_{C1}+V_{C2}+V_{C0} = a\ V_{A1}+a^2\ V_{A2}+V_{A0}$; $a = 1\ \angle 120$, $a^2 = 1\ \angle 240$

For fixed components in power systems, like cables, lines and transformers, the positive sequence impedance is equal to the negative sequence. In rotating machines like synchronous generators and induction motors the positive sequence is not equal to the negative sequence impedance and usually obtained from testing the machines under the two different conditions.

The short circuit calculations are performed for the first ½ cycle using the subtransient reactance of the generators in the system and this value is used for sizing all equipment to withstand the momentary and close and latch current ratings obtained; the mechanical forces on the elements of the system are proportional to the peak of this short circuit value. The short circuit calculations are also performed for 3 or 5 or 8 cycles from fault inception and about 30 cycles from time of fault. The former calculation produces a value that is used when deciding on the interruption rating of the breaking device (breaker or fuse) as this is the current under which the breaking device contacts staets to get apart/breaks or the fuse starts to melt that will cause the ionization in the current path and at current zero, this arc has to be extinguished and stay like that so that the fault is isolated. In this case, the transient reactance of the generator is used (if a generator is part of the system under study). The latter is calculated with the synchronous reactance of the generator in the model and is calculated to give an indication of the short circuit level in the case of a delayed tripping (fault breaking) or reclosing. The fault calculations have to be made assuming faults at two locations, one close to the source and another at the end of the line (to get the minimum expected fault current, so that the sensitivity of the fault sensing element can be checked). The integration of the power loss I^2R over the period that the short circuit exists is an indication of what thermal ratings (withstandability) that the components (in the system) in the faulty path have to withstand. Short circuit currents are given in KA root mean square (rms) and sometimes in KA peak. They are also given as symmetrical or asymmetrical. The duration of asymmetry (which means the current wave is sinusoidal but offset from the x-axis (not symmetrical around the x-axis) depends on the X/R (reactance to resistance ratio of the elements in short circuit path). The short circuit current will start as asymmetrical if the fault occurs at any point on the voltage wave other than the peak assuming a reactive path and as times in cycles progress, the wave changes into symmetric due to the fact that the d.c. component (the cause of asymmetry) decays in the resistance (R) component of the path. When ground faults occur, this means a single phase to ground (eg. failure of a cable/splice or an insulator or even a flashover), double phase to ground or 3 phase to ground, the fault current will flow back to the neutral of the source supplying the fault. The fault current magnitude will depend on the ground resistance, and the method of the neutral grounding of the source transformer. The method of grounding the neutral of the source will also affect the voltage on the unfaulty phases during the fault of one phase to ground. The methods of neutral grounding are solidly (no intentional resistance or reactance between the neutral and the ground), effectively grounded (low reactance inductor is connected between the neutral and ground) which means that under all conditions and on any point of the system the ratio of the zero sequence reactance to the positive sequence reactance is less than 3 and the ratio of the zero sequence resistance to the positive sequence reactance is less than 1, high resistance grounding (a resistance to limit the current under single phase to ground to lets say 5 amp, thus for a 3 phases 600V system a 69.4Ω resistor would be required). When a single phase to ground fault occurs, if the system is solidly grounded, then the voltage on the unfaulty phases (during the fault) will be maintained at phase to neutral value; if the system is effectively grounded, then the unfaulty phases will have 80% the line to line voltage and finally for ungrounded or high resistance grounded neutral, the voltage on the unfaulty phases will be at a level equal to the line to line one. The methods of detecting the phase to ground faults are function of the method of grounding and the available sensing devices, though they are classified into direct, where the sensing current transformer is included in the neutral-to-ground connection and the sensor is connected to the overcurrent relay; the vectorial summation (zero sequence) method, where the zero sequence current transformer is installed in such a way as to have all the 3 cables of the 3 phases plus the neutral passing through the opening of the C.T. and this C.T. is connected to the relay and the final method is the residually connected current transformers,where the C.T.s are connected in parallel (zero sequence filter) then are fed into the overcurrent sensing relay. In a distribution system and when faults occur downstream on a line the earth (ground or soil) resistance is in the path of the return current (fault), thus it has to be kept to minimum low (especially in effectively neutral grounded system) to offer a low ground return path to the current. Soil or ground affect power system distribution in 3 main areas which are: class of soil that indicates the type and degree of strength, this consequently affects the installation methods of poles (towers) and their guying methods (using anchors and guy wires), thermal resistivity of soil which affects the current carrying capacity of underground cables and finally its electrical resistance that is function of the material, the season, the number of pipes (rods) or plates buried every mile or Km, the interconnection of the pipes (to form a type of parallel connection) to further reduce the resistance and the length of the ground rods. The soil resistance can be measured using a megger and 4 electrodes methods.

<u>1-1 Causes of faults in power systems:</u> they can be classified into: application, operation, exposure and workmanship. Faults in power systems happen anywhere, in any component whether installed indoor or outdoor. The location of the fault and the component type where the fault occurs may dictate the type of protective device to be used eg. if the fault occurs outdoor and is expected to be of a transient nature, then an overcurrent relay (delayed plus instantaneous) can be used plus a reclosing scheme, on the other hand if the fault is of permanent nature like those happening is transformers, generators, bus ducts than a fast operated (eg. zone differential relay) instantaneous can be applied. The misapplication of any of the components building a power system can be the reason for a failure eg. if a post insulator is selected and if the operating voltage and the power frequency overvoltage/impulse voltage exceeds the insulator rating, flashover will occur thus a short circuit is established between the phase and ground. Then the source starts supplying the fault. Another example would be the use of cables/splices that are underrated when it comes to continuous currents, overload currents and fault currents. If a breaking device like a circuit breaker is used in a system where the overvoltages occurring, during switching or because of natural phenomena (lightning), exceeds the breaker rating, failure (fault) in the breaker may occur. Another cause of failure may be the quality of power supplied, as harmonics causes failure to certain components in a power system, surges and sags, also may be the direct or indirect cause of failure. Overvoltages and their causes will be covered in details in Chapter 5, Transients in Power Systems. The second cause of failure in power systems are the operation of breaking devices (breakers, load break switches and fuses). As mentioned above when a circuit breaker is operated to trip open a circuit, overvoltages are induced in the system, this occurs when switching nominal load currents or fault currents, thus stressing the other components in the system and the circuit breaker itself. The cause of the overvoltage is not the circuit breaker itself, though the distributed (or lumped) capacitance and inductance of the circuit elements on the load and line (supply) sides. Switching capacitive and inductive currents (closing and opening) impose more severe overvoltages on the system components. In fuses, the blowing of one or two fuse elements out of the 3 in a 3 phase system may cause overvoltages (ferroresonance condition) that may cause failure of insulation and thus a fault starts. When operating the transformers at a higher than nominal voltage for long periods of time i.e. setting the tap changer at a 5% or 16% (for example) tap, stressing the insulation (eg. bushings or oil) and eventually, a fault may occur. The third cause of faults in power systems is exposure and with exposure, it is meant the presence of corrosive gases in the vicinity of the insulators. It also means, exposure to other environmental pollution like dust, smoke or environment conditions like rain, fog, ice, snow. Exposure to trees or heavy traffic or even animals, all these factors, in overhead distribution systems, have to be considered as potential causes of failure (function of the degree of exposure). For direct

buried cables, the exposure degree comes from the chance of digging into a cable. Exposure of all outdoor equipment to weather conditions impose a hazard and may cause transformer or padmounted switchgear failure due to direct hits in a lightning storm. The last reason that may cause faults in power systems is workmanship. Workmanship can be broken down into: during manufacturing, during installation and finally maintenance (operation and related activities). During manufacturing, the cause of failure can be the use of wrong or underrated component, inadequate assembly, lack of proper testing to detect the defects before shipping to final destination. Each component during assembly (at certain stages during the assembly process), in general, is tested and after final assembly (if applicable) another set of tests are usually performed. During installation, if the right procedure is not followed, premature failures can occur causing faults. For example, the proper torquing of hardware in bus assembly or connectors, the use of the right compression tool and compression force onto the compression lugs, the right position of aluminum conductor with respect to copper when both are installed in the same connector (to avoid cold flow). The last point which is operation/maintenance, with the right maintenance programs for the different equipment in the power system and adhering to such programs (modified to include for changes in equipment testing, models and inspection methods), such programs may lead to the forced failures in the power systems being minimized or the elimination of the forced outages for certain components in the system. Another way to classify the causes of faults is to which category of the following, the failure is attributed to: insulation, electrical, mechanical or thermal reasons. The causes that are pertinent to the first are: design defects, improper manufacturing or installation, aging; the second are: lightning surges or switching overvoltages, the third are: wind, snow, ice, contamination and for the last are: overcurrent, overvoltage.

I-2 Radial power systems modelling: when it comes to modelling power systems for fault studies, the first thing that should be decided is which method of calculation is going to be used i.e. circuit reduction (the manual method) or the impedance network model of the system (which may be applied to personal computers, so that all the calculations are performed by the PC - executing instructions and juggling variables, memories and registers). The data required for such study are the reactances (or impedances) of all components in the system including the tap changers (when included with transformers) and from the single line diagram, a single phase reactance diagram is constructed. When the fault is assumed to happen on a bus the sequence networks for such condition are constructed and connected with each other depending on the type of fault as shown in Chapter 2, section I-4-4). They are connected between the faulty bus and the neutral. This is applicable to the circuit reduction method. Using the delta to wye and wye to delta transformation (as explained in Chapter 2, Section 1-4-3) plus the combination of parallel and series reactance branches, the circuit will be reduced to the voltage source in perunit (prefault voltage level at the fault) and one reactance element representing the positive sequence network, one representing the negative sequence network (if required, function of the type of fault) and one representing the zero sequence plus the fault reactance and the neutral reactance (whichever applicable to the type of fault and availability in the system). The primary, secondary and teritiary transformer winding connections will affect the zero sequence reactance and thus the flow of the zero sequence current (representing ground fault) from one side of the transformer to the other. The most commonly applied transformer connections are: wye-wye (isolated neutral), wye (isolated neutral)-wye (grounded neutral), wye-delta, delta-wye (grounded neutral), wye (isolated neutral)-zig zag (grounded) neutral. For the representation of certain common connections, click here. To clarify the circuit reduction method, assume a system having on one end a generator rated 30MVA, 13.8KV, 3 phases with a subtransient reactance (+ve sequence) = 15%, -ve sequence = 15% and zero sequence =

8%, the generator is connected to a delta wye transformer rated 13.8KV/220KV, 40MVA, impedance .11 p.u., resistance = .0036 p.u., X/R = 30, the transformer then feeds a transmission line assume 80 ohm positive sequence and negative sequence impedance (reactance) and 250 ohm zero sequence reactance. This line ends in a wye grounded - delta transformer with 220/13.8KV other ratings are identical to the generator one. This last transformer then feeds 2 synchronous motors with the following characteristics: motor 1: 20MVA, 13.8KV, positive sequence reactance = .2 = -ve sequence and the zero sequence = .08 p.u., motor 2 is rated 15MVA, other ratings similar to motor 1. The neutral of the generator and motor 1 are grounded through a 2 Ω current limiting reactors. Calculate the line to ground and line to line faults for this system.
For the positive and negative sequence networks: The base MVA = 30, the base KV on the generator and motor sides = 13.8KV, on the line side = 13.8 (220)/13.8.
Reactance of transformer = $(.11)^2 - (.0036)^2 = .1099$ (or .0036x30) (based on the transformer rating).
0.1099 (30/40) = .817 p.u. based on 30MVA
Reactance of motor 1 = .2 (30/20) = .3 on $30MVA_b$
Reactance of motor 2 = .2 (30/10) = .6 on $30MVA_b$
Z,sub>base = $(KV_b)^2/MVA_b = (220)^2/30 = 1613$ Ω|line side
Reactance of line = 80/1613 = .0495 p.u.
For the zero sequence network: reactance of the line = 250/1613 = .155p.u.
Reactance of neutral reactors = $3Z_n$=3x2/Z,sub>b/motor or gen. Side
$Z_b = (13.8)^2/30 = 6.348$W
Thus reactance of reactors = 3x2/6.348 = .945 p.u.
Reactance of transformer = .0817 p.u.
Reactance of motor 1 = .08 (30/20) = .12 p.u.
Reactance of motor 2 = .08 (30/10) = .24 p.u.
The j for the reactance is omitted for convenience.
Calculate the reduced (the equivalent) circuit of the positive sequence network: (the same is applicable for the -ve sequence): $1/R_1 = 1/.3 + 1/.6 = .9/.18$; R,sub>1 = .2 p.u.
$R_2 = .2 + .0817 + .0495 = .3312$ p.u., R3 = .0817 + .15 = .2317 p.u.
$1/R_4 = (1/.3312) + (1/.2317)$; $R_4 = .136$ p.u.
+ve seq. reactance = -ve seq. reactance = .136 p.u.
Zero seq. reactance = (.0817) (.155+.0817)/.0817+.155+.0817) = .061 p.u.
Thus for a <u>line to ground fault</u>, the magnitude of the fault current = $[V_{prefault}/X_1+X_2+X_0]3$ = 3/.333 = 9 p.u.
For the <u>line to line faults</u>, only the positive sequence and negative sequence networks appear in the calculation (equation), more will be said about types of faults later in this chapter under Section 1.4.
$I_{A1} = 1/(Z_1+Z_2) = 3.7$ p.u. (magnitude)
$I_{A1} = I_{A2} = 3.7$ p.u., fault currennt = $I_b = -I_c$ assuming phases b and c touching each other.
$I_B = a^2\, I_{A1}$ + a I,sub.A2; and $I_{A0} = 0$
$(-.5-j.816)\ (j3.7) + (-.5 +j.866)\ (-j3.7) = I_B$;
Thus the magnitude of the fault current = 6.41 p.u. In case a personal computer is available to run these studies on, then the impedance model has to be used. The impedance network model was covered in

Chapter 2, Section 1-4-7. Using this approach, the voltages on the unfaulty buses can be obtained systematically as is shown in Section 1-4 later in this chapter. To model a system for such a method, the same data as the circuit reduction method would be required.

I-3 Grid power systems modelling: the data required to perform fault studies on grid systems are more or less similar to those required for radial systems. The difference is in the degree of complexity of the grid having more than one source, feeding the connected loads at the same time. The method best suited for grids is the impedance network. The neutral is taken as the reference node (node 0) and then the buses are numbered sequentially, each load bus, generator bus, motor bus (if applicable). For the synchronous machines, the subtransient reactance is used to calculate the short circuit current during the first cycle (momentary, close and latch ratings of breaking devices), the transient reactance to calculate the short circuit current during the 2nd or 3rd cycle up to the eighth cycle (breaking devices interrupting rating) and finally the synchronous reactance to calculate the short circuit current for delayed tripping. For the induction motor and to calculate its contribution for the first few cycles, the transient reactance is used in the calculation. For stationary components like overhead conductors, underground cables, transformers, the impedance or reactance of the component is used. The procedure for building the impedance network is given in Chapter 2, Section I-4-7 and the types of calculations will be given in the next section. Parallel circuits, lines connecting, lets say, bus 1 to bus 3 and bus 1 to bus 2 can be presented in this model.

I-4 Types of faults calculations: the purpose of fault calculations is to get the magnitude of the short circuit current and the voltage on the buses, other than the faulty (in radial systems will be for those upstream the faulty bus, in grid systems, it will be for the upstream as well as the downstream faulty bus). The voltage sensitivity calculation in this section will only be limited to the two types of faults the most probably will happen (single phase to ground) and the most severe (3 phase faults).

•• Radial systems:

For line to ground faults: (examples: failed cable or splice, broken insulator or insulator flashover, reduced clearances, failed single phase transformers, etc.)

The calculations here will be given for 4-bus radial system (for one feeder, as during faults the feeder with the fault is important and is part of the study the system with the others either supplying the fault with motor contribution or they are not part of the study - if there are no source of short circuit current). The effect of motor contribution will be covered later when grid systems are covered.

Step 1: construct the impedance network (that will be also used with other types of faults for +ve, -ve and zero sequence). The fault is assumed to be on bus 4.

$X_{111} = XX_{011}+XX_{121}+XX_{231}+XX_{341}$

$Y_{24} = XX_{011}+XX_{121}$

$Y_{34} = XX_{011}+XX_{121}+XX_{231}$

$$Z_{bus\,+ve} = \begin{bmatrix} XX_{011} & XX_{011} & XX_{011} & XX_{011} \\ XX_{011} & XX_{011}+XX_{121} & Y_{24} & Y_{24} \\ XX_{011} & Y_{24} & Y_{34} & Y_{34} \\ XX_{011} & Y_{24} & Y_{34} & XX_{111} \end{bmatrix}$$

where XX_{011} is the +ve sequence reactance between node 0 and bus 1, XX_{121} between bus 1 and 2, XX_{231} between bus 2 and 3, XX_{341} between bus 3 and 4 (even if the feeder had more buses, the calculation would stop here - as the voltage on the downstream buses will be equal to that of the faulty as long as there is no motor contribution from the downstream buses), a similar negative sequence impedance model can be constructed.

$$Z_{bus\,-ve} = \begin{bmatrix} XX_{012} & XX_{012} & XX_{012} & XX_{012} \\ XX_{012} & XX_{012}+XX_{122} & Y_{242} & Y_{242} \\ XX_{012} & Y_{242} & Y_{342} & Y_{342} \\ XX_{012} & Y_{242} & Y_{342} & XX_{112} \end{bmatrix}$$

where $XX_{112} = XX_{012} + XX_{122} + XX_{232} + XX_{342}$

$Y_{242} = XX_{012} + XX_{122}$, $Y_{342} = Y_{242} + XX_{232}$

For the zero sequence network, it's a little bit tricky as the connections of the transformer and neutral grounding method (if applicable) have to be taken into consideration when building the zero sequence impedance matrix. If the transformer connection (it is assumed in this example system that the transformer is connected between node 0 and bus 1) is such that for a single phase to ground, the fault current will have no path to ground eg. wye-wye (isolated ground), delta-delta, wye (grounded)-delta, wye (grounded)-wye then the short circuit (fault) current = 0. A zig-zag transformer connection can replace a delta and it will provide the same phase angle between the primary and secondary windings and will provide a neutral terminal. If the transformer is connected delta - wye (grounded) or wye (grounded) - wye (grounded) the zero sequence impedance network matrix has to be built for each case including the source (system ahead of the transformer) of short circuit capacity or the generator (ahead of the transformer, if applicable). The relevant elements for the first transformer connection are: $X_{110} = XX_{010} + XX_{120} + 3(d) + XX_{230} + XX_{340}$

$Y_{240} = XX_{010} + XX_{120}$, $Y_{140} = XX_{010} + 3(d)$

$Y_{340} = XX_{120} + XX_{230} + XX_{010} + 3(d)$

As the example, here, is a special condition that the supply of the short circuit current can supply infinity amperes, then the equations for the grounded wye-grounded wye transformer connection will be identical to the above condition.

XX_{010}: is the zero sequence reactance between node 0 and bus 1.

XX_{120}: is the reactance between 1 and 2, and so on.

d: is the reactance in the ground (fault) current path.

Step 2: From above the short circuit current for a fault on bus 4 = $3\,(V_f)/(X_{111} + X_{112} + X_{110})$. For the voltage sensitivity calculations, the full set of equations are given in the "Example programs" section later in this chapter, here only the set of equations to calculate the voltage at bus 1 will be given to correlate between the elements given in the above sequence networks and the equations:

$V_{S10} = -Y_{140}\,(I_{fault})/3$, $V_{S11} = V_f - Y_{14}\,(I_f/3)$

$V_{S12} = -\,(I_f)\,(Y_{142})/3$, $V_{SAf} = V_{S10} + V_{S11} + V_{S12}$

$V_{SBr} = V_{S10} + (-.5)\,(V_{S11}) + (-.5)\,(V_{S12})$

$V_{SBi} = (-.866)\,(V_{S11}) + (.866)\,(V_{S12})$

$V_{SBf} = [V_{SBr})^2 + (V_{SBi})^2]$

$V_{SCr} = V_{S10} + (-.5)\,(V_{S11}) + (-.5)\,(V_{S12})$

V_{SCi} = .866 (V_{S11}) + (-.866) (V_{S12}); where V_{S10}: zero sequence voltage on bus 1, V_{S11}: +ve sequence voltage, V_{S12} is the -ve sequence voltage, V_{SAf} is the voltage on phase A of bus 1, V_{SBf} is the voltage on phase B, V_{SCf} is the voltage on phase C.

For 3 phase faults:

The S.C. fault current = V_f/X_{111}

The voltage on bus 1 = V_f $(1-Y_{14}/X_{111})$ in p.u.

The voltage on bus 2 = V_f $(1-Y_{24}/X_{111})$ in p.u.

The voltage on bus 3 = V_f $(1-Y_{34}/X_{111})$ in p.u.

For line to line faults:

The fault current = $(.866)(2)(V_f/(X_{111}+X_{112}))$

For line to line to ground:

I_{nt} = Intermediate value = $V_f/[X_{111} + (X_{112})(X_{110})/(X_{112}+X_{110})]$

The fault current = $3 (I_{nt}) (X_{112})/(X_{112} + X_{110})$

•• Grid or network systems:

The analysis hereafter will be based on a hypothetical system having the following components: a synchronous generator between bus 1 and the reference node 0, other sources of fault currents are between buses 2 and reference node and another one between bus 3 node 0. The last 2 sources can be squirrel cage induction motors and the fault current is to be calculated for the first few cycles (i.e. if there are generators in the circuit, their reactance will be the subtransient for the calculation of the fault current during the first few cycles and the transient value for the next period in the short circuit duration) with motor reactance equal the transient one (afterwhich the contribution of the SCIM is reduced to 0 - in a few cycles from fault inception). The other components are lines between the following buses: 1& 2, 2 &3, 3 & 4, 1 & 4, 2 & 4. The full set of equations to solve this network is given in the “Example Programs” section.

The impedance matrix is calculated based on the process given in Section 1-4-7 in Chapter 2 and will have the following form:

$$Z_{bus\,+ve} = \begin{bmatrix} XXC_{11} & XXC_{12} & XXC_{13} & XXC_{14} \\ XXC_{21} & XXC_{22} & XXC_{23} & XXC_{24} \\ XXC_{31} & XXC_{32} & XXC_{33} & XXC_{34} \\ XXC_{41} & XXC_{42} & XXC_{43} & XXC_{44} \end{bmatrix}$$

The same format can be used to build the negative and zero sequence networks:

For line to ground fault on bus 3:

$I_f = 3 (V_f)/(XXC_{33} + XXC_{332} + XXC_{330})$

The voltage sensitivity calculations can proceed following the steps given under radial systems.

For line-line-line fault on bus 3:

$I_f = 1/XXC_{33}$

For line to line and double line to ground faults: the equations given in the radial system can be applied here.

All the faults covered so far were of the *parallel type*, the series types can be classified into single and double opened phases (in case of a blown fuse or a broken connector or line). The purpose of such calculation is to know the negative sequence current in the unopened phases and consequently the currents in the B and C phases, assuming A is the opened phase. By the same reasoning, the positive, negative and zero sequence voltages are obtained and consequently V_A, V_B & V_C become known.

Knowing the negative sequence current in such a circuit can decide on the setting of the negative sequence overcurrent relay if used as part of the protection scheme. The use of such relay is common with S.C.I.M. and synchronous generators protection.

Step 1: For a broken wire (let's say phase A), the positive sequence current in phase A, the zero sequence current and the negative sequence current will be calculated from the currents in phases B, C and the neutral (if applicable).

Step 2: For the broken wire, the voltages on phases A, B & C are calculated through the knowledge of the positive, negative and zero sequence voltages in phase "A". From the knowledge of the sequence voltages, the sequence currents can be calculated. Now as V_A, V_B & V_C are known downstream the broken point, V_{A1}, V_{A2} & V_{A0} can be calculated. From the ratio of the negative sequence voltage to the positive sequence and when multiplied by the ratio of the reactance of the S.C.I.M. at starting to its reactance at normal speed (which is equal to the ratio of the starting current to its full load current), the negative sequence current in the motor (in amps.) can be obtained by multiplying the p.u. value by the motor full load current. The case of the open conductor is similar to the single phase to ground boundary conditions i.e. for a broken wire, $I_A = 0 = I_{A1} + I_{A2} + I_{A0}$, $V_{pp'C} = 0$, $V_{pp'B}= 0$ where V_{pp}' is the voltage between the fictitious broken wire in phases B and C, (for a single line to ground $I_B= I_C=0$, $V_A = 0$ assuming zero fault impedance). For the open phase condition:

-Calculate the prefault current flowing between the 2 buses, the open point is in between those 2 buses of the open phase .

-Obtain the +ve, -ve and zero sequence impedance for the section between buses 2 & 3. The impedance matrix of the system is available.

-Calculate the positive, negative and zero sequence impedances between the open points (pp')

$Z_{pp'1}= - Z_1{}^2/Z_{n-1/n-1}{}^1+Z_{n/n}{}^1-2Z_{n-1/n}{}^1-Z^1$

the same equation is used to calculate the -ve and zero sequence impedances but replacing the +ve sequence values with the corresponding - ve or zero sequence.

-The positive sequence voltage drop across pp' in phase "A" = -ve sequence voltage = zero sequence = $I_{n-1/n}[(Z_{pp}{}'^0.Z_{pp}{}'^1.Z_{pp}{}'^2)/(Z_{pp}{}'^0.Z_{pp}{}'^1+Z_{pp}{}'^1.Z_{pp}{}'^2+Z_{pp}{}'^2.Z_{pp}{}'^0)]$

$-V_n = V_{pf} + \Delta V_n$, $\Delta V_n = \Delta V_{n1} + \Delta V_{n2} + \Delta V_{n0}$; ΔV is the change in the symmetrical components volatages of phase "A" voltage due to the open circuit condition.

$\Delta V_n = [Z_{n/n-1} - Z_{nn}] V_A/Z$ for the +ve, -ve and zero sequence components. For complete example programs solving short circuit problems, click here.

Contents

CHAPTER 4
LOAD FLOW STUDIES

I- Power Section:

Load flow studies are performed on power systems to assist in specifying the rated continuous (nominal) currents of the different equipment and components in the system. The studies are performed taking into account all possible switching configurations and the different possible paths of power in the system. It may be performed to examine the effect of adding capacitors (distributed over the system or concentrated at the station) in improving voltage levels, increasing capacity of line (feeder) and reducing reactive power flowing from source (improving power factor). It may also be performed to see the starting effect of motors on the levels of voltage all over the system (at the different buses). The admittance network matrix will be used in such studies (given in section I-4-8 of Chapter 2). The types of main buses in load flow study single line diagrams are: the generator, the load and the slack (only one). At the generator bus, the known variables are: the voltage and the active power, the calculated ones are: the phase angle and the reactive power. For the load, the known variables are the active (real) power and reactive (which are scheduled at the bus and are kept constant over the period of the study - the calculations can be repeated with other values and a new study for the same system is generated). For the slack, the voltage and the phase angle are known and kept constant over the period of the study (usually 1 p.u. and 0). Beside the above mentioned required data for each type of bus, the following are also required in order that a load flow study can be run on a system: the admittance matrix for the system's buses including the resistance, inductive reactance and capacitive reactance of the line (or cable); the reactances of all the machines in the network and the tap changer ratio (eg. 2.5% x 2 above and 2 below).

I-1 Methods and equations for the load flow calculations: the methods that may be used to solve the nonlinear algebraic load flow equations are Gauss, Gauss-Seidel, Newton Raphson and the decoupled method. The nodal current equations for n bus in a system are written as follows:

$I_p = \sum_{q=1}^{q=n} Y_{pq} V_q$; $p = 1, 2, 3, \ldots$ Y_{pq} is the admittance between bus p & q and V_q is the voltage of bus q.

$I_p = Y_{pp} V_p + \sum_{\substack{q=1 \\ q\neq p}}^{n} Y_{pq} V_q$; $V_p = I_p/Y_{pp} - (1/Y_{pp})\ \Sigma Y_{pq}\ V_q$

$S = VI,\ S = P + jQ,\ S^* = P - jQ$

$V_p^* I_p = P_p - jQ_p,\ V_p = (1/Y_{pp})\ [(P_p - jQ_p)/V_p^* - \Sigma V_{pq} V_q]$

-Gauss Method

Step 1: Assume a flat voltage profile for all nodal voltages except the slack. The slack bus voltage and angle will remain the same for the duration of the study and they do not change with iterations. Set the maximum acceptable level (absolute value) of voltage difference between any two consecutive iterations for all of the buses in the study (convergence criteria).

Step 2: For all buses other than the slack, calculate the bus voltage; V_p^{k+1} and the difference in bus voltage between the two consecutive iterations $\Delta V_p^k = V_p^{k+1} - V_p^k$ Go to the next bus and evaluate V_p^{k+1} & ΔV_p^k.

Step 3: When all buses are evaluated, find ΔV_{max} (largest absolute value of change in voltage). If $\Delta V_{max} < \varepsilon$, the voltages, angles and power flow in the lines can be calculated. These equations will be given later in Sections 1-2 and 1-3.

-Gauss Seidel Method (including generator bus type)

Step 1: Assume a flat voltage profile for all nodal voltages (except the slack). Set the convergence criteria.

Step 2: For voltage controlled buses (generators): before getting into the process of calculation for such buses the following equations are to be noted:

The admittance between any two buses can be expressed as: $G_{pq} + (-jB_{pq}) = Y_{pq}$, the voltage of any bus can be expressed as: $V_p = e_p + j f_p$ and Q_p as: $\Sigma\ f_p (e_q G_{pq} + f_q B_{pq}) - e_p (f_p G_{pq} - e_q B_{pq})$, the derivation of the latter equation can be found in any of the references listed at the end of this chapter. Replace the value of the voltage magnitude in the iteration by the specified value for the generator bus eg. 1.04, 1.06,..etc), keep the phase angle the same as in the iteration (for the first iteration the angle δ = 0). Calculate Q for the generator bus. The value can either fall within the lower and upper values of Q as specified for the study or outside this range. This range is set so that stability of the system is maintained (the minimum value) and rotor heating of the synchronous generator is not excessive (set the maximum value). If Q fell in the range, calculate the new value of the bus voltage. When calculating the voltage of the buses for the other loads or generators, the specified voltage is used with the angle obtained from this iteration. If the Q as calculated does not fell within the range, the bus will be treated as load bus and the magnitude of the reactive power at this bus will correspond to the limit it has violated, the value of the voltage (magnitude) will correspond to the value in this iteration (1 p.u. for 1st iteration) and then continue with the other generators or loads buses. Note if more than one generator (bus) exists, when calculating Q at the specific bus, only V_{spec} of this bus will be used while for the other generator buses the voltage obtained from the previous iterations will be used.

Step 3: For the load buses: calculate V_p^{k+1} , for bus p and iteration number K+1, find $\Delta V_p^k = V_p^{k+1} - V_p^k$. Find the largest of the absolute value of the change in voltage (between 2 consecutive iterations). If this value is less than ε , then register the voltage and angle of each bus in the system and calculate the power flow between the buses. The process of convergence can be accelerated if the ΔV during consecutive iteration is modified: $V_{pacc}^{k+1} = V_p^k + \alpha\ \Delta V^k$, where α is the acceleration factor, a suitable value may be 1.6.

-Newton Raphson method: the equations used with this method are:

When no generator bus exists: $\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta e\\ \Delta f\end{bmatrix}$; J is the Jacobian matrix (first derivation matrix).

When all types of buses exist, including generator ones:

$$\begin{bmatrix}\Delta P\\ \Delta Q\\ \Delta V\end{bmatrix} = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\\ J_5 & J_6\end{bmatrix}\begin{bmatrix}\Delta e\\ \Delta f\end{bmatrix}$$

The residual column vector consists of ΔP, ΔQ & ΔV_p; where $\Delta V_p = P_{sp} - P°$, $\Delta Q_p = Q_{sp} - Q°$ $|\Delta V_p|^2 = V_{sp}^2 - |V_p°|^2$; $P_{sp}/Q_{sp}/|V_{sp}|$ are the specified quantities (scheduled values for load buses) at a bus p, the required increment voltage vector contains Δe and Δf, $e_p^{k+1} = e_p^k + \Delta e_p$, $f_p^{k+1} = f_p^k + \Delta f_p^k$ The J matrix will have diagonal and off diagonal elements for each subscript i.e. the diagonal elements of J_1:

$\delta P_p/\delta e_p = 2 e_p G_{pp} + \Sigma (e_q G_{pq} + f_q B_{pq})$; where the B symbol represents the susceptance of the line, G represents the conductance, pp are the self values and pq are the transfer values between bus p and bus q.

$|V_p|^2 = e_p^2 + f_p^2$; $V_p = e_p + j f_p$; $Y_{pq} = G_{pq} - j B_{pq}$

The diagonal elements of J_2:

$\delta P_p/\delta f_p = 2f_p G_{pp} + \Sigma (f_p G_{pq} - e_q B_{pq})$

The diagonal elements of J_3:

$\delta Q_p/\delta e_p = 2e_p B_{pp} - \Sigma (f_q G_{pq} - e_q B_{pq})$

The diagonal elements of J_4:

$\delta Q_p/\delta f_p = 2f_p B_{pp} + \Sigma (e_q G_{pq} + f_q B_{pq})$

The diagonal elements of J_5:

$\delta |V_p|^2/\delta$ e,sub>p = $2e_p$

The diagonal elements of J_6:

$\delta |V_p|^2/\delta f_p = 2f_p$

The off-diagonal elements of

J_1: $\delta P_p/\delta e_q = e_p G_{pq} - f_p B_{pq}$, where q is not equal p

J_2: $\delta P_p/\delta f_q = e_p B_{pq} + f_p G_{pq}$, where q is not equal p

J_3: $\delta Q_p/\delta e_q = e_p B_{pq} + f_p G_{pq}$, where q is not equal p

J_4: $\delta Q_p/\delta f_q = - e_p G_{pq} + f_p B_{pq}$

J_5: $\delta |V_p|^2/\delta e_q = 0$

J_6: $\delta |V_p|^2/\delta f_p = 0$

In summary, this is an iterative method which approximates the set of nonlinear simultaneous equations to a set of linear simultaneous equations using Taylor's series expansion (the terms are limited to first approximation).

The steps to solve the simultaneous equations using this method are as follows:

Step 1: Assume a suitable voltage level (that for example 1 + j 0) for all buses except the slack, which will stay constant as specified until the end of the study. Set ε (convergence criteria), if the largest of

the absolute of the residue (P & Q) is less than ε at the end of any iteration, the process stops and the values of V, δ and the power flow levels are registered and calculated, respectively.
Step 2: For all buses, except the slack, the real and reactive powers are calculated. The real power residue ΔP_p is evaluated = $P_{scheduled} - P_p^k$.
Step 3: If the bus is a generator one, Q_p^k; is compared with the acceptable range (upper and lower limits). If the limit is not violated, evaluate the voltage residue $\Delta |V_p|^2 = |V_{psch}|^2 - |V_p^k|^2$. If the reactive power at this bus is violated, set the reactive power generated to the limit (either upper or lower, for whether the upper or lower limit has been violated), the bus is treated as a load bus for this iteration.
Step 4: ΔQ_p^k is evaluated to $Q_{sch} - Q_p^k$. The largest of the absolute of the residue is compared with ε, if the former is less than the latter, the voltage and angle at the different buses are registered and the power flow values are calculated. If it is the other way around then Δe_p^k and Δf_p^k (voltage increments) are calculated, the new bus voltages are calculated:
$e_p^{k+1} = e_p^k + \Delta |e_p^k$, $f_p^{k+1} = f_p^k + \Delta$ f,sub>p^k. The Jacobian matrix elements would have been already evaluated and cos δ & sin δ are evaluated for all voltages. A new iteration is underway starting from Step 2 above.

-Fast decoupled method: It is based on the fact that a small change in the phase angle will only affect (change) the flow of active power but it will not change the reactive power flow. A small change in bus (nodal) voltage will affect only the flow of reactive power. Using polar coordination ($\angle\ \theta$):

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & 0\\ 0 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix}$$

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}H & 0\\ 0 & L\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta|V|/|V|\end{bmatrix}$$ or it can be written as $\Delta P = H\,\Delta\delta$ & $\Delta Q = L\,\Delta|V|/|V|$

$P_p = |V_p V_p Y_{pp}| \cos \theta_{pp} + \sum |V_p V_q Y_{pq}| \cos(\theta_{pq} + \delta_p - \delta_q)$

$Q_p = |V_p V_p Y_{pp}| \sin \theta_{pp} + \sum |V_p V_q Y_{pq}| \sin(\theta_{pq} + \delta_p - \delta_q)$

further assumptions may be made to simplify the calculations: $\cos(\delta_p - \delta_q) = 1$, $G_{pq} \sin(\delta_p - \delta_q) < B_{pq}$; $Q_p << B_{pp} Vp^2$.
L_{pq} (off diagonal element of L) = H_{pq} (off diagonal element of H) = $H_{pq} = |V_p V_q|[G_{pq} \sin(\delta_p - \delta_q) - B_{pq} \cos(\delta_p - \delta_q) =$
$H_{pp} = L_{pp}$ (diagonal elements) = $- V_p^2$ B,sub>pp

I-2 Radial power systems modelling: radial distribution power systems will have transformers, overhead lines, generators, motors, cables that are connected in series and shunt capacitors connected most probably in parallel (shunt). Overhead lines will have capacitance to ground that may affect the calculation of the study, as well as cables. If transformers have tap changers, this has to be taken into consideration while building the admittance matrix of the system. For a single feeder system with a few load buses and slack bus at the secondary of the transformer feeding such loads, the data required to perform a load flow study are the series resistance and reactance between the slack bus and the next one and between every 2 consecutive buses, the VA_c (volt ampere capacitive) of the equivalent lumped capacitance at each bus, this represents the distributed capacitance of the line, the voltage profile for the first iteration for the load buses and the constant voltage for the slack bus, the phase angle at all buses (voltage is usually taken as 1 p.u. and angle as 0). The active and reactive power at the load buses (entered with a -ve sign as these are loads). From the data known, as mentioned above, the following values are calculated: Z_{n-1} to n which is the impedance between every 2 consecutive buses = $[(r)^2 + (X)^2]^{.5}$, than the admittance is calculated Y = 1/Z, the impedance angle is calculated an = $\tan^{-1}$ X/r, the conductance between the consecutive buses are calculated from g = Y cos(- a_n), the susceptance = Y sin(- a_n), then the lumped capacitance at each bus is calculated Yc = $VA_c/2\ VA_{base}$. Now, the construction of the admittance matrix is starting g,sub>b = the off diagonal elements (conductances) in the matrix and is equal the conductance between the subject buses (transfer conductance), g_{bb} is the self conductance of the bus i.e. all the conductances connected to the bus are added together (and are the diagonal elements in the matrix), the same is applicable to the susceptance (b_b and b_{bb}, for transfer and self susceptance) component of the admittance matrix except that the transfer susceptance are entered with a -ve sign. Now at each load bus, the difference between the calculated and scheduled (specified) active power is obtained which is the residue active power. The following prototype equation may be used for each bus: $P_b = g_b (V_s)^2 + V_s (V_n) (-Y_b) (\cos - a_n + \delta_n - \delta_s) + V_s (V_{n+1})(-Y_b')(\cos -a_n + \delta_{n+1} - \delta_s)$; where g_b is the self conductance for the bus under consideration (eg. for bus 2 is g_{b22}), V_s is the voltage for this iteration for the bus under consideration, V_n and V_{n+1}, are the voltages for the buses upstream and downstream the one under consideration (V_s), a_n is the impedance angle for the link (section) between the 2 buses, δ_s is the phase angle of bus with V_s voltage, d_n and d_{n+1} are the phase angles for the upstream and downstream buses (for the first iteration the voltage = 1 p.u. and angle = 0, for slack they remain constant through out the study at these values). The difference between scheduled and calculated = $diff_p = (P/100) - P_b]/V_2$; assuming VA_{base} = 100 MVA. Depending on the number of equations to be solved which is function of the number of the buses in the system the method of solution of the B (Susceptance) matrix will be chosen. For 2x2 or 3x3 (excluding the slack bus, the total number of buses are 2 or 3) the inversion of the matrix procedure is used as given in Chapter 2, Section 1-4-5. If the number of buses are more than 3, then the triangular factorization method is used as explained in Section 1-4-6 of "a href = "cpfpsq02.html">Chapter 2.

The output of the solution of the B matrix is the phase angle increment ($\Delta\ \delta$) of each load bus that has to be added to the new d value (usually in radians and then the final value can be converted into degrees). The prototype equation may look something like this $\delta_{new}^{k+1} = \delta_{old}^{k} + \Delta\ \delta^{k}$. At this stage, the difference between the scheduled reactive power (specified) at each load bus and the calculated is to be obtained. The following equation is used:

Δ $q=[q/100)+(bb_s)(V_s)^2+V_s V_n(-Y_b)(\sin -a_n +\delta_{n-1}^{k} + \delta_s^{k+1})+ (V_s)(V_{n+1})(-Y_b')(\sin -a_n + \delta_{n+1}^{k} - \delta_s^{k+1})](1/V_s)$

From this set of equations and the B matrix, that was already solved and used with diff p (active power residue matrix) to obtain $\Delta\ \delta^k$, $\Delta\ V^k$ is obtained and then $V^{k+1} = V^k + \Delta\ V^k$. The output of the first iteration (V and δ) are used in the next iteration in the same manner as that shown above until V^{k+1} - $V^k < \varepsilon$ and Q^{k+1} - $Q^k < \varepsilon$. At this stage the power line flows are calculated using the final values of V and δ. The prototype equations for the active power flow from bus n to n + 1 and vice versa are:

$P_{n\ to\ n+1} = V_n{}^2(g_{n\ to\ n+1})+(V_n)(V_{n+1})(-Y_{n\ -\ n+1})(\cos\text{-}an_{n\ -\ n+1} + \delta_{n+1} - \delta_n)$.

$P_{n+1\ to\ n} = (V_{n+1})^2(g_{n\ to\ n+1})+V_n(V_{n+1})(-Yn - n+1)(\cos\text{-}an_{n\ -\ n+1} + \delta_n - \delta_{n+1})$.

The same can be done for the reactive power as follows:

$Q_{n\ to\ n+1} = -(V_n)^2(b_{n\text{-}n+1} + Y_c)\text{-}V_n(V_{n+1})(-Y_{n\text{-}n+1})(\sin\text{-}an + \delta_{n+1} - \delta_n)$

$Q_{n+1\ to\ n} = -(V_{n+1})^2(b_{n\ -\ n+1}+Y_c)\text{-}V_n(V_{n+1})(-Y_{n\ -\ n+1})\ (\sin\ \text{-}an + \delta_n - \delta_{n+1})$.

Other common radial systems may have the slack bus connected to the primary of a power (or distribution) transformer with the secondary connected to a common bus to which 4 or 5 feeders are connected, the same approach used with the single feeder can be applied here modifying the equations to suit the present system. The examples given in "Example programs", Section II of this chapter show all the equations and procedure required for a couple of common radial systems configurations. The method used to solve for radial systems in this book is the fast decoupled, while on the other hand for the grid (network) systems, the Newton Raphson method is used. If the snap shot approach to the effect of starting a motor in the system is applied, then the motor data required is its reactance in p.u. based on the base values used for the subject study. In general for load studies, motors are represented as a constant power devices in steady state analysis while for their effect under starting conditions are represented as constant impedance. The self susceptance of the bus having the starting motor will be modified accordingly $bb_s=bb_{n+1\ -\ s} + bb_{n\ -\ s}$/motst; where $bb_{n+1\ -\ s}$ is the susceptance between the subject bus and the bus downstream of it, $bb_{n\ -\ s}$ is the susceptance between the subject bus and the bus upstream of it and motst is the motor reactance, the term motst is entered with a -ve sign. If the effect of the capacitor that is added to the subject system is to be investigated, its reactance is entered in the same way as the motor starting one though with a +ve sign. All the real and reactive power taken from the system at the different load (or other) buses are entered with a -ve sign, the generated power values (at generator buses) are entered with +ve sign. For an example of a simple radial system, click here.

I-3 Network (grid) power systems modelling: the components that may cconstitute such a system are generators, lines, cables, loads. The slack bus is usually taken as one of the generator buses existing in the system. The data required would be the inductive reactances, resistance and capacitive reactances of all the elements in the system. Also, the voltages and angles of all buses for the first iteration (as mentioned previously - the values for the slack bus remain the same for the total number of iterations of the study). If the MVA_{base} is other than 100 MVA, it should be specified plus the KV_{base}, active and reactive power scheduled (required or generated) at the different buses. Newton Raphson iterative method will be used here. The self and transfer conductances and susceptances for all the system buses will be calculated and the admittance matrix is built. The active and reactive power residue matrix (vector) - mismatches - will be calculated which includes the difference between the scheduled and calculated values for all the buses. As mentioned previously one of the generator buses is taken as the slack, in this case there is only one more generator bus. The Jacobian matrix for this system (with total number of buses = 4) is:

$$\begin{bmatrix} M_{22} & M_{23} & M_{24} & MM_{25} & MM_{26} & MM_{27} \\ M_{32} & M_{33} & M_{34} & MM_{35} & MM_{36} & MM_{37} \\ M_{42} & M_{43} & M_{44} & MM_{45} & MM_{46} & MM_{47} \\ N_{22} & N_{23} & N_{24} & NN_{25} & NN_{26} & NN_{27} \\ N_{32} & N_{33} & N_{34} & NN_{35} & NN_{36} & NN_{37} \end{bmatrix}$$

&

where bus 1 is taken as slack and bus 4 as voltage controlled i.e. generatorone:

$M_{22} = V_2(V_1)(-Y_{12}\ \sin\text{-}a_{n12}+\delta_1-\delta_2)+V_2(V_4)(-Y_{24}\ \sin\text{-}a_{n24}+\delta_4-\delta_2)$,

$M_{33} = V_3(V_1)(-Y_{13}\ \sin\text{-}a_{n13}-\delta_3+\delta_1)+V_4(V_3)(-Y_{34}\ \sin\text{-}a_{n34}-\delta_3+\delta_4)$,

$M_{44} = V_2(V_4)(-Y_{24}\ \sin\text{-}a_{n24}-\delta_4+\delta_2)+V_4(V_3)(-Y_{34}\ \sin\text{-}a_{n34}+\delta_3-\delta_4)$,

$M_{23} = -V_2(V_3)(-Y_{23}\ \sin\text{-}a_{n23}-\delta_2+\delta_3)$,

$M_{32} = -V_2(V_3)(-Y_{23}\ \sin\text{-}a_{n23}-\delta_3+\delta_2)$,

$M_{24} = -V_2(V_4)(-Y_{24}\ \sin\text{-}a_{n24}-\delta_2+\delta_4)$,

$M_{42} = -V_2(V_4)(-Y_{24}\ \sin\text{-}a_{n24}-\delta_4+\delta_2)$,

$M_{34} = -V_4(V_3)(-Y_{34}\ \sin\text{-}a_{n34}+\delta_4-\delta_3)$,

$M_{43} = -V_4(V_3)(-Y_{34}\ \sin\text{-}a_{n34}+\delta_3-\delta_4)$,

the above terms are related to the reactive power (Q).

$N_{22} = V_2(V_1)(-Y_{12}\ \cos\text{-}a_{n12}+\delta_1-\delta_2)+V_2(V_4)(-Y_{24}\ \cos\text{-}a_{n24}+\delta_4-\delta_2)$,

$N_{33} = V_3(V_1)(-Y_{13}\ \cos\text{-}a_{n13}-\delta_3+\delta_1)+V_4(V_3)(-Y_{34}\ \cos\text{-}a_{n34}-\delta_3+\delta_4)$,

$N_{23} = -V_2(V_3)(-Y_{23}\ \cos\text{-}a_{n23}+\delta_3-\delta_2)$,

$N_{32} = -V_2(V_3)(-Y_{23}\ \cos\text{-}a_{n23}-\delta_3+\delta_2)$,

$N_{34} = -V_3(V_4)(-Y_{34}\ \cos\text{-}a_{n34}-\delta_4+\delta_3)$,

$N_{24} = -V_2(V_4)(-Y_{24}\ \cos\text{-}a_{n24}-\delta_2+\delta_4)$,

$N_{42} = -V_2(V_4)(-Y_{24}\ \cos(-a_{n24}+\delta_2-\delta_4)$

the previously mentioned terms are active (real) power related,

$MM_{25} = N_{22}+(2V_2^2)(gb_{22})$,

$MM_{26} = -N_{23}$, $MM_{35} = -N_{32}$, $MM_{36} = N_{33}+ 2V_3^2(gb_{33})$, $MM_{45} = -N_{42}$, $MM_{46} = -N_{34}$, $NN_{25} = -N_{22}-2V_2^2(bb_{22})$, $NN_{26} = M_{23}$, $NN_{35} = M_{32}$, $NN_{36} = -M_{33}-2V_3^2\ bb_{33}$.

The column pertinent to bus 4 (a generator bus) = 0. The above matrix is then solved as a 5x5 matrix or 5 simultaneous equations to be solved using triangular factorization, this process will be repeated for every iteration. The elements in the upper and lower matrices are obtained (as mentioned in Chapter 2, Section 1-4-6) and then are used with the P and Q mismatches to obtain the ΔV and $\Delta\delta$ to be added to those used at the beginning of the iteration to get the new (closer to the final solution) values of V & δ that will be used in the next iteration. When the final solution is obtained, the active and reactive

power flowing between the buses (from which the losses in the line are found) as given in the previous section, are calculated. For a simple grid system, click here.
Complete example programs in Quickbasic and C++

Contents

CHAPTER 5
TRANSIENTS IN POWER SYSTEMS

I- Power Section:

The causes of transients in power systems are numerous and can be classified into external or internal (due to components making part of the system) causes. The main external cause is lightning. Lightning can cause over voltages on the line because of direct hits to the line or indirect hits nearby the line. The internal causes can be due to switching operations, failure of equipment or components. Switching operations can further be classified into energizing (switching on) or de-energizing (switching off) of inductive and capacitive circuits. The transient voltages imposed on the system can be classified into high frequency over voltages or power frequency, the details will be given in Section I.2 later in this chapter. Over voltages in power systems may occur due to resonance between the inductance and capacitance (eg. transformers and cables) not only at the power frequency but also at harmonics exciting (applied to the circuit) voltages.

I.1 Overview of power systems components modelling for transients analysis: transients that are caused due to internal causes can be due to the operations of a circuit to isolate a fault - transient recovery (restriking) voltage. It can also be caused when a circuit breaker extinguishes the arc, then restrikes (reconducts), multiple re-ignition may cause over voltages (high frequency) or if capacitor banks are switched a voltage buildup will occur across the breaker contacts at power frequency if restriking occurs. Over voltages also occur due to current chopping or virtual chopping and current limiting effect of breaking devices. Under certain conditions and if one or two of the three phases of the breaking devices are opened, over voltages may occur (ferroresonance). The mere switching on and off (energizing and de-energizing) loads like capacitors and inductive devices will cause overvoltages in the system. Modelling of the system to study its behaviour will vary depending on the stimulus (event creating the disturbance) and the expected output of the study. Transients study is important in order to enable the design of a reliable system and to be able to anticipate the system performance under the different types of overvoltages that are imposed on the system. The model of each component will vary depending on the type of study. Terminal models will have R, L&C elements per component and then terminals of the components are interconnected together. Only those components that are effective to a study are included in the circuit with only the attributes of such components that are influential to the stimulus. The next step performed on the circuit for transients analysis is the circuit reduction (the re-arrangement and the collapse of the elements). The following steps can be used as a guideline when preparing an equivalent circuit of a system for a transient study:

Step 1:Set the boundary of the system under study (eg. replace the sources by infinite buses), components and attributes.

Step 2:Set down the circuit (model) representing each component in the system.

Step 3:Decide on the method, either π or T for representing the lines, windings, cables, etc.

Step 4:Capacitances at the points where they join can be combined together.

Step 5:When the top and bottom halves of the circuit are identical, when looked at from the point of disturbances, the circuit can be folded on itself along its horizontal centerline. This process will allow certain elements to be paralleled and others eliminated.

Step 6:Perform the reasonable (justifiable) approximation to reach the final circuit upon which the study is performed.

The two analytical tools most used in transients analysis are: the Laplace transform (which solves the differential equation by transforming them to algebric ones) and the symmetrical components. The elements used to represent power systems components are the combination of any of: resistances, inductances and capacitance and are usually combined to form series or parallel circuits. The exciting voltage (or current) in a circuit can take any shape, function of time. Using Laplace transform, it is transferred to the S-domain, example of such functions are given hereafter:

-a step wave (the constant V): £V $= \int_0^{\infty} V e^{-st}\, dt = V/S$

- a ramp (a current ramp I't): £I't = $I' t e^{-st}\, dt = I'/S^2$

-an exponential wave from: £$e^{\alpha t}$ =£$e^{\alpha t} e^{-st}\, dt = 1/(S - \alpha)$ for $S > \alpha$; for £$e^{-\alpha t}$, the Laplace transform = $1/(S + \alpha)$

- for a sin wave: $\sin \omega t = (e^{j\omega t} - e^{-j\omega t})/2j$, £$\sin \omega t = \omega/(S^2 + \omega^2)$

- a cosine wave: $\cos \omega t = (e^{j\omega t} + e^{-j\omega t})/2$, £$\cos \omega t = S/(S^2 + \omega^2)$

- a derivative form (1st, 2nd, etc): £F''(t) = S £F(t) - F(0) £F''(t) = S² £F(t) - S F(0) - F'(0)

- an integral: £$\int_{-\infty}^{t} F(t)\, dt = (1/S)$ £$F(t) + (1/S) \int_{-\infty}^{0} F(\tau)\, d\tau$

The following time constants are worth remembering: $T = (LC)^{.5} = (T_p T_s)^{.5}$, $T_p = RC$ which is the parallel circuit time constant, $T_s = L/R$ which is the series circuit time constant in 1/time dimension.

The other parameters are: the surge impedance = $Z \eta^2 = T_p/T_s = R^2 C/L = 1/\lambda^2$.

There are three basic Laplace transforms (and inverse transforms) encountered in the RLC circuits. Refer to reference [1] (list of references at the end of this chapter) for such equations.

Each of the three expressions will yield three different solutions depending on the parameter η ($\eta > ½$, $\eta = ½$ and $\eta < 1/2$). Practical examples in which these equations will appear are, respectively, when the current of a capacitor will discharge in the other parallel elements in which I_L (inductor current) is calculated, the capacitor voltage is to be found and finally when a parallel RLC circuit is excited by a ramp shape current. For sketches of common RLC circuits, click here. Symmetrical components were covered in Chapter 3 "Faults in Power Systems", this method can be applied to transients analysis where the natural frequency of the oscillations (that constitute the transient) are resolved into +ve, -ve and zero sequence components. The sequence components do not interact in a symmetrical system. Using this method when analyzing transients, when a circuit breaker is interrupting a downstream fault, opening the pole in phase A is simulated by inserting an impedance Z between the contacts in that phase. $V_A = I_A Z$, $V_B = V_C = 0$ as the other two poles of the circuit breakers are assumed to be arcing (or still closed), $V_0 = 1/3\ [V_A+V_B+V_C\}$, $V_1 = 1/3\ (V_A + a V_B + a^2 V_C]$, $V_2 = 1/3\ (V_A + a^2 V_B + a V_C)$; where V_0, V_1 & V_2 are the sequence voltages, $V_0 = V_1 = V_2 = V_A/3$. $I_A = I_0 + I_1 + I_2 = V_A/Z$. In terms of sequence impedance networks: $V_0 = I_0 Z_0$, $V_2 = I_2 Z_2$, $V_1 = E_1 + I_1 Z_1$. The sequence networks must include the capacitances of the system. The sequence impedances (Z_0, Z_1, Z_2) are those seen looking into the balanced system through the contacts of any phase of the breaker. The interconnection of the sequence networks will reflect the type of fault downstream to be cleared (eg. for 3-phase fault, are connected in parallel, for single phase fault, are connected in series). The transient voltage is equal the sum of the responses of the separate networks. If the circuit breaker clearing the fault is not located at the fault, the sequence components of current must be injected at the breaker terminals in each phase sequence and the recovery voltage of the breaker will be the sum of these three responses. The classical method of calculating the transient recovery voltage for breakers opening under faulty conditions is the circuit reduction method which will be covered briefly in the next Section I-2, later. Modelling of the following components of a power system may be deemed necessary to analyze a system under transient conditions (steep front voltage wave, transfer of surges, etc): transformers, generators, motors, transmission lines and cables. The details of such approach are given in Reference [1]. Here, only, a brief coverage will be given. The capacitance of a winding is function of its geometry (the physical position of the turns and coils relative to each other and the grounded parts of the structure). The two principle types of windings are the layer and the disk, for transformers. A generator, generally, has more coils than a transformer though are connected in parallel. A turn in a generator can be divided into a straight section in the slot (significant capacitance to the grounded slot wall and to other conductors in the slot) and the end connection (less capacitance to the frame and more mutual capacitance with other conductors in the overhang- end-region). Hydro generators, in general, have shorter slots and longer end sections than turbo ones with more turns per coil. Motors on the other hand have a number of coils in series of which the coils themselves have a number of turns.

-Transformer modelling: there are three principle types of transformer models, each one is used to study specific transient condition. They are the complete, internal model, the terminal and the surge transfer through a transformer model. The internal is used when it is required to study the internal voltage distribution and oscillations within the transformer when it is subjected to different stimuli. The terminal model is used when a line is terminated by a transformer and the study would involve the effect of the transformer or switching surges, surges due to faults and voltage experienced by lightning arresters protecting the transformers. The complete model is rarely used due to its complexity and the most of the studies would only required the approximated or the other models. The simplest model is for a transformer while is unloaded at the end of the line and is switched. The transformer will act as an open circuit to the stimuli, the equivalent circuit will be a parallel circuit of RLC. The other models may involve dividing the duration of the study into intervals and having a model (circuit) for each interval. The surge transfer model acts as a filter that passes certain frequencies and attinuate others.

-Generator modelling: two common models of generators for transient studies are one for oscillatory disturbances and another for fast rising transients. The first is caused by de-energizing generator/transformer units. The last is caused by reignition process in the breaking device or fast rising surge coupled capacitively through the unit. For very fast transients, eddy currents prevent the immediate penetration of flux into the stator iron. For the first stimulus, the model will include resistance in series with leakage inductance and capacitance per phase, the mutual inductance between the phases can be presented by a factor in the phase circuits or the neutral one. For fast transient models, they include the conductor in the slot that is represented like a transmission line (π or T); if a short transmission line is represented then the inductance will only be considered, the same is used with the overhangs (end connections). With fast transient and in slot conductor, the magnetic flux is confined within the slot (screened from stator iron by the eddy currents) initially. In this case the surge impedance is low. For the end connections, Z_0 is higher since the inductance is high and the capacitance is low.

-Modelling of motors: most motors are connected to their supply by a cable. A traveling wave will pass down the cable and impact the motor. The three common models for motors are: the terminating

impedance, the short sections of transmission line presentation and multiple π sections plus the resistance/inductance/capacitance blocks for the different frequencies available in the system (5 blocks or 3 blocks decided from the frequency scan of the machine).
-Modelling of overhead lines: an elaborate model has to take into consideration the modes of propagation and the effect of the different (natural) frequencies on the line parameters. Another model is a resistor equal to the line surge impedance. In general, a transmission line is presented as a T or π circuit for one frequency or as a terminal model. The frequency scan of a line would reveal an infinite number of natural frequencies occurring at regular intervals along the frequency axis. Single conductor modeling is much simpler than actual circuits like 3 phase lines, single or double circuits with or without ground wires and the effect of ground. The details are beyond the scope of the presentation of this topic, here. The references listed at the end of this chapter may be consulted for such details.
-Modelling of underground cables: for transient analysis, cables can be classified into: single phase shielded or not, 3 phase (triplexed) shielded or not and belted cables. In shielded and grounded cables the electric field is confined between the current carrying conductor and the shield, although the magnetic field is not confined as a portion of the current of phase A may be returning in phase B. One model may be a resistor equal the surge impedance of the cable. Capacitance of cables is enhanced by the permitivity of the dielectric (ε =3.5 or 4) which also reduces the speed of propagation of the wave along the cable. The second model can be a presentation of the cable by a capacitor (in parallel with the load), this model is used for low frequency transients that may be caused by switching a load connected to the supply by a cable. The third model which is used, when fast transients effects are to be investigated, is the distributed model. The use of the equations of the network performance under steady state (relating terminal conditions of a line or cable) can be the starting point in obtaining the parameters (inductance and capacitance). These equations (2 of them) related the sending voltage with the receiving one as well as the sending current with the receiving current. Other variables used in the equations are the propagation constant = $(Z\ Y)^{.5}$, the length of cable or line and the characteristics (surge) impedance.
-Other models for the core (iron) used in transformers and motors, potential and current transformers, line traps, bus ducts and capacitor banks may have to be built in order to be able to analyze fully a system for transients responses.

I-2 Common operations that cause over voltages in power systems: broadly, the causes can be the energization or de-energization of the different zones in a system under normal loads or faults, lightning and failures (permanent or temporary) of components in a system.
• Energizing an inductive circuit: this phenomenon of over voltage due to inductive circuits energization happens to single and three phase configurations. For a single phase, immediately following the closing of the switch, the joint voltages (source and load) seeks coincidence with the steady state through a transient over voltage stage. In the theoretical case of loss-less circuit, the transient will carry the voltage above the source peak voltage by an amount equal to the original difference between the voltage that is function of the distributed load and source capacitances and the supply voltage at switching time. The typical maximum over voltages encountered in such circuits is 2 times peak for 100% overshoot, 1.6 times for 60% overshoot. For a three phase, the highest possible over voltage will occur in the case when phase A is closed at a time following the prior closing of phases B&C. The typical maximum over voltages expected are 2.5 x peak voltage for 100% overshoot and 1.9 for 60% overshoot.
• Energizing a capacitive circuit: for a single phase circuit, if the velocity of the closing switch is slow compared to the frequency of the power supply, the closure will be accomplished by a sparkover of the

closing contact at or near the peak voltage. At the instant of closing, the source voltage drops to zero (at the first instant of closure the capacitor appears to the source as a short circuit). The steady state voltage is reached through over voltage oscillations. The levels of over voltages are: 2 x peak voltage for 100% over voltage and 1.6 x peak for 60% overshoot. For a 3 phase capacitive circuit, the maximum over voltage will occur when the switch is closed at the peak voltage value of one phase after the other two phases have been already closed. At the instant of closure, the source voltages of the 3 phases are equal 0. In swinging back to their steady state, an over voltage of 2 times the peak appears on phase A (without damping) and 60% overshoot ratio will produce 1.6 times over voltage.

• De-energizing an inductive circuit: the main cause of over voltage caused when a circuit is switched off (de-energized) is restriking caused in the switching devices due to the distributed load and supply capacitances plus the inductances in the circuit. Other causes of over voltages when circuits are de-energized are: current chopping and virtual chopping. When de-energizing a single phase inductive circuit, the following phenomena will occur: the load voltage will reach zero through high frequency oscillation due to the presence of distributed capacitance on the load side of the switching device, on the supply side the voltage will attempt to reach the no load level but still through an oscillation. The restriking (reconduction of the gap in the switching device) may occur at the worst condition of which the gap is subjected to the highest voltage difference (between the contacts of the load and supply sides) and at that point the potential on the load and supply sides will join and, instantaneously, become coincident. The voltage will reach its steady state through over voltage transients. The level of over voltage for lossless circuit is 3 times steady state peak (100% overshoot) and 1.96 times for 60% overshoot. For a 3 phase circuit, de-energization of the inductive load and assuming that phase A current will be interrupted at value 0, the voltage on the load side of phase A will overshoot. The supply side voltage will tend toward the source voltage through over voltage (transients) oscillation. A restrike at the peak of the transient recovery voltage will bring the source and load sides of phase A of the switching device together through transient oscillating over voltage. If phase A is to stay interrupted, then phases B & C will interrupt the currents flowing through them at current 0, (restriking will cause over voltages on phases B & C). On phase A, the over voltage may reach 4 times peak normal voltage for 100% overshoot and 2.4 for 60%; phase B or C will reach 2.56 times peak value and 1.7 times for 100% and 60%, respectively.

• De-energizing a capacitive circuit: with certain interrupting media in the switching devices, multiple re-ignition (at power frequency), phenomena may occur. It means a sequence of current interruptions and conductions causing successive build up of voltage on the capacitor being switched. After interruption in a single phase circuit, the recovery voltage across the contacts of the breaking device will build up until restrike occurs. Since the capacitor capacitance is much higher then the equivalent capacitance of the source side, the voltage on the source side will shift instantly to join the voltage on the load side of the switching device. A transient will carry the voltages on the load and source sides to its steady state conditions. The over voltage may reach 3 times peak at 100% overshoot and 2.2 times at 60%. For three phase circuits, if the neutral is grounded, the circuit behaves like 3 independent single phase circuits. With ungrounded neutral, the time of restriking has to be assumed and then the circuit analyzed. Though, the general process will be as follows: after the interruptions of the phase currents, the recovery voltages will build up across the poles of the switching devices. At the moment of the restrike, the recovery voltage across the switching device contacts will disappear. The source voltage and load voltage merge. Transient over voltage will occur until the steady level is achieved. For a 100% overshoot, the typical over voltages will be on phase A 2.9 times peak and 2.4 - 3 times for phase C; for

60% overshoot, phase A will see 2.15 times and phase C 1.65 times peak normal voltage.
I-3 Rate of rise of restriking voltage: the traveling wave method and the reflection/refraction factors at every junction point plus the lattice network construction can be used to obtain the voltage levels under different operating conditions at the different buses of the network. In this section the equations used in the short method for calculating the rate of rise of transient recovery voltage, restriking voltage level and time to peak will be given:
RRRV = .8 (KA) (Z_{total})/1000 KV/μ sec

KA: short circuit fault current for 3 phase ungrounded fault.
Ztotal = (simp/nb) + simp/(2 nb), simp: surge impedance of line, nb = number of lines connected to the bus at time of fault.
Time in μ sec. to first cycle crest voltage = 2 (10.7) distance, distance in miles from fault to first open point (circuit).
Crest (peak) voltage of first crest = 800 (KA) (leq) (1+Z/nb) in KV, leq is the parallel inductance of all sources connected to the main bus at time of fault.

I-4 Quantifying lightning strikes: when lightning hits directly an overhead line, the voltage wave will travel across the line function of the steepness of the front of wave of the current hitting. At the first support, if the basic impulse level is exceeded and no surge (lightning) arresters are installed, flash over will occur. If the lightning is hitting close to the line, induced over voltage will be imposed on the line and the BIL of the structure has to withstand the induced over voltage otherwisw flash over will occur. The equations that are used to quantify such incidents are:
-direct hit: Minimum distance between lightning arresters to avoid flash over = sol (sil) (ttp)/(simp.psc)
psc: peak (crest) stroke current sil: structure insulation level ttp: shape (front of wave) of stroke (time to peak) sol: speed of light -indirect hit:
induced overvoltage = 20 (h) (1.2) (cur)/X
h = height of phase conductor from ground
X = distance of striking point from phase conductor
cur = stroke current

I-5 The effect of the L.A. lead length on overvoltages: the overvoltage imposed on the protected equipment because of the lead length of the lightning arrester connecting the live terminal to one side of the L.A. plus the lead connecting the other terminal of the L.A. to the ground plane = len (cur)/tim; where len is the L.A. lead (conductor) inductance per unit length, tim is the front of wave shape of the current (stroke) wave (eg. 4, 8, 1.5 msec.) and cur is the maximum (peak) curent flowing through the L.A. Complete example programs in Quickbasic and C++

Contents

CHAPTER 6
RELIABILITY STUDIES

Reliability studies are classified into reliability studies for industrial/commercial/institutional and utility applications. The main input to such studies are, for the different types of equipment and devices: the rate of failure per year (number of failures per year in decimal) and the average number of hours of forced outage per failure for the components. The output will give for the component and for the system the total number of hours per failure per year and for the system the failure rate. The data required and included in the system will vary based on the study approach used. The approaches used in such studies are: the minimum cut set, network reduction and static space approach. A complete reliability analysis of a system may include the preventive maintenance issues, emergency stand-by power design, planning and designing for a reliable plant or evaluating and improving the reliability of an existing system. The preventive maintenance program would include: inspection, testing, cleaning, drying, monitoring, adjusting, repair service library, failure investigation, records system and training. The emergency and stand-by power systems selection is function of the load (availability vs quality) requirements, the failure rate, the failure duration. Planning and designing for a reliable plant process may include preliminary designs of the plant and the economical results evaluation of the different options. From such analysis the acceptable economical design that provides the required technical properties to the distribution system can be selected. A typical procedure is:
-assigning costs to all individual items involved in the system under study.
-assign a value to the lost production time less expenses (saved due to outage).
-assign costs (values) saved along with those incurred from the expected restart time and cost of repair (or replacement time).
-assign costs for damaged plant equipment, extra maintenance required, cost of repair of failed component and for the use of off-specification products.
-determine the total investment of each alternative, variable expense, fixed investment charge factor and finally calculate the minimum revenue requirements of each alternative.
The evaluating and improving the reliability of an existing system can be approached by going through the following steps:
-decide on the ideal system operation conditions.
-decide and evaluate the system physical conditions.
-evaluate the consequences of faults on all the buses or load centers in the system.
-evaluate the failure rates and duration for all the components in the system.
-decide on the equipment or components in the system that are most vulnerable or hazard to the health and safety.
-decide on the failures that cause major financial losses.

I-1 Modelling of industrial power systems: The different available configurations of industrial power distribution systems are: the simple radial system, the primary selective to utility supply system, the primary selective to primary of transformer system, the primary selective to load side of main medium voltage service entrance circuit breaker system and the secondary (low voltage side) system. From the single line and the 3 line schematic (or wiring diagrams) of a system, the following data are to be obtained: the series elements per circuit (minimum cut set method), that if any component will fail an outage will occur at the bus under study (whether the service entrance, main or any other bus in the system), their failure rate and outage hours per failure. If for the same project, more than one alternative configuration exists, then the data mentioned previously should be available for each alternative. The utility data for the industrial plant supply, can be obtained from the electric utility company. The major components that may build a series path of an electrical distribution circuit are: Protective relays, power and distribution transformers, low voltage and medium voltage circuit breakers, low voltage and medium voltage bus bars in switchgear assemblies, underground and in air cables, low voltage and medium voltage cable splices. The calculations can be classified into 5 types (as the mentioned previously type of systems), one for simple radial, another for primary selective to utility supply, one for primary selective to load side of M.V. circuit breaker, primary selective to primary of transformer and last secondary selective. Another criteria for the availability of a stand-by source would be to speed the switching over from the faulty to the available source i.e. instantaneous (0 delay) vs. delayed or timed (eg. 9 minutes, 3 minutes, etc).

I-2 Modelling of utility systems: For a typical layout of a utility feeder, click here. For a utility system, where radial systems are in use, more than one feeder will be going out of the transformer station (or the distribution station). The series path of a feeder circuit may include the following: the high voltage disconnect switch, the high voltage insulation, the lightning arresters, the power transformers, the medium voltage bus duct, the medium voltage switchgear complete with the breakers and insulated main bus, the underground medium voltage cables and splices, the poles, the insulators, riser pole or distribution type lightning arresters, the load break switches, cable terminations, padmounted switchgear, distribution transformers (pole mounted, padmounted, vault installed) and overhead conductors. For each feeder a number corresponding to its reliability can be obtained and a comparison of this number for the different feeders will indicate, the weaker ones, thus steps to improve the reliability number (i.e. reliability) of such feeder can become possible. From the same approach the total number of customer outages hours can be calculated. The other approach to analyze a utility system reliability would be similar to that of an industrial system, where the rate of failure per component and per ft for overhead and underground segments in the system plus the average outage hours per failure per component or foot can indicate the reliability of each feeder. For the first approach the number to be used have to be consistent for all feeders and these numbers are: exposure factor of the overhead line (which include for trees density, traffic density, animal availability, lightning storms, frequent switching), conductor factor (function of the material and the protection method of the conductor), sectionalizing/upstream protection device factor (function of fuse sizes, transformer station protective device settings, the use of reclosures and sectionalizes), the weighted number of customers interrupted for the section that becomes faulty. Other important factors to be taken into consideration while modeling are the total number of taps (branches) from the main lateral, its length as well as the factors mentioned in the previous sentence. For the second approach, in addition to the failures data required for the equipment and auxilliary elements, the following are necessary: total number of lines/cables network related failures per year, average downtime hours/failure, total length of overhead conductors plus the underground cables. The calculation of the total number of failures per year per unit length and the underground cable factor (which is function of method of laying cable, equipment to pull cables or excavate and cable splicing method, fault location/indication methods) are necessary to complete the analysis. Complete example programs in Quickbasic.

Contents

Chapter 7
STABILITY CALCULATION

Stability studies are classified into steady state and transient. The first being the stability of the system under conditions of gradual or relatively slow change in load. The second is the limit of maximum power flow through a point, at which sudden or large changes in network conditions occur that will still not cause a loss of stability in the system. One of the reasons for performing such studies is the adjustment of relays (protective and reclosing), as the protective relays have to operate to isolate a fault (or a disturbance) before the loss of stability (falling out of synchronism of the generators). If stability is function of the speed of operation of the reclosing relays, than the appropriate setting of the speed of the relay has to correspond to the closing time that will avoid a complete collapse of the system. The stability of a generator can be indicated by having a curve with the x-axis corresponding to the torque (power) angle and the y-axis to the power transferred from bus 1 to bus 2. The maximum power transferred = $(V_1.V_2/X_{12})\sin\delta$, where δ = 90 and $\sin\delta$ = 1, after which an oscillation will take place in the synchronous machine rotor and if the machine to fall out of step the power output will start decreasing until it reaches 0 (at which δ (the rotor angle) =180). The system disturbances that cause the power angle to increase (oscillate and then return to steady state or increase until loss of stability) are: short circuits, loss of a tie circuit to a public utility (equivalent to adding load to local generation), loss of a portion of an on-site generation, starting a motor which is large in relation to the system generating capacity, switching operations in general, abrupt decrease in electrical loading of generators, the abrupt additional mechanical (impact) load on electrical motors. In general, stability problems can be classified into calculating: inertia constant from the moment of inertia, the equivalent inertia constant for 2 parallel units (machines), load angle equation under normal and faulty conditions, frequency and period of oscillation of a machine under slight temporary disturbance, critical clearing angle and time under three phase fault, swing equation for multi machine system during and post fault.

I-1 Modelling power systems for certain disturbances: In general, the data required to perform a stability study can be classified into data: pertinent to the system, to the load, to the type of disturbance and to the type of rotating machine i.e. synchronous machines (major and minor) and induction machine (major and minor). The system data can further be classified into: impedance of all significant cables, transmission lines, reactors and other series components, impedance of transformers, and auto transformers, also KVA rating, voltage ratio, winding connections, available taps, regulation range, tap step size and type of tap changer control, steady state short circuit capacity of utility supply, KVAC of all significant capacitor bank, description of normal and alternate switching arrangements. Regarding the load data, the following are essential: real and reactive power of the loads at all the significant buses in the system. For the major synchronous machines (or groups of identical machines at a common bus), the following data are required: mechanical and/or electrical power ratings (KVA, HP, KW); inertia constant (H) or inertia WK^2 of the rotating components of the electrical machine, load and prime mover; speed, active and reactive loading (for motors only, the speed torque curve), direct axis subtransient, transient and synchronous reactances, direct axis and quadrature-axis subtransient and transient time constants; saturation information (no load and air gap characteristics E_f vs. I_f or mmf) and Potier triangle (short circuit characteristics of the m/c); damping data and excitation system time constant and limits; governor and steam systems (or another prime mover type) time constants and limits. In minor synchronous machines, the data required are: mechanical and/or electrical power ratings; inertia, speed, direct axis synchronous reactance. For major induction machines or groups of machines, the data are: mechanical and/or electrical ratings; inertia, speed and positive sequence equivalent circuit data; load-speed-torque curve; reduced voltage (starting arrangement, if any). For minor induction machines, the data required are the static presentation of the motor. If one machine, only, is considered in a multi machine system (during and post fault), it would send into the interconnected system an electromechancial oscillation in the order of 1 to 2 c/s. This oscillation is determined by the inertia and synchronizing power of the machine. The typical steps used in stability calculations are:

-Calculate the steady state prefault condition for the power flow in the network (Chapter 4 covered load flow studies).

-Build the prefault network as well as during fault and postfault (after fault isolation) networks.

-Calculate the transient internal voltage of each generator (V_t+IX_d'); V_t is the corresponding terminal voltage, I is the output current.

-Convert each load to a constant admittance (to ground) Y=(P-jQ)/V, P+jQ is the load and V is the corresponding voltage of the load bus.

-Calculate the power flow of each generator into the network, $P=V_n^2G_{nn}+V_nV_{n+1}[Y_{n-n+1}\cos\delta_{n-n+1}-\&\theta_{n-n+1}]+...$; $\delta_{n-n+1}=\delta_n-\delta_{n+1}$

-Put the swing equation of each generator during disturbance (fault or the like) and post disturbance (switching or fault), swing equation = $(2H_m/W_s)(d^2\delta/dt^2) = P_m{}^n-P_e{}^n$; where n=1,2,3...

I-2 Equations used in the stability equations: In general the calculation will be based on the following variables: the clearing time in second from fault inception to clearing (or the duration of the disturbance) and the time interval selected for the study (a typical value is .05 sec.). The output of the calculation will be a table or graph showing the time from the start of the disturbance to the return of the steady state against the power angle of the generator under study (the angle between the rotor axis and the reference rotating at synchronous speed (or infinite bus voltage). In the following discussion the disturbance will be assumed to be a fault that is cleared and the angles (power or torque-as sometimes termed) at the specified intervals will be calculated assuming a certain time delay for the fault to clear. If the angles converge over the time, then the system is assumed to be stable under such disturbance and conditions, if the angle diverge the system is unstable under the specified conditions. The power angle values have to be calculated 20 or 30 times at .05 sec. intervals and if they converge over a period of time this does not mean that the system is stable. The convergence may be followed by a divergence (δ increases over the period), followed by another convergence. Thus a suitable duration over which the study is performed, has to be selected at the beginning of the study. The input data for such a study would be:

-time interval selected for the study in sec.

-the clearing time of the fault in sec. (The operating time of the breaking device plus the delay of the protective relay).

-the inertia constant of the generator H in MJ/MVA

-at time of fault (or time of disturbance):

- the mechanical input to the generator (P_m)
- the initial rotor angle (in deg.) for the machine (δ)
- the maximum power transferred (E_1E_2/X)
- the P_c parameter (E_1 E_1 G,sub>11)
- the phase angle θ ($\tan^{-1}$ X/R)
-after fault clearing (after the termination of the disturbance).
- the mechanical input to the generator
- the maximum power transfer
- the P_c parameter
- $\tan^{-1}$ X/R
- the frequency of the system.

The following parameters are then calculated during the fault: $P_e^1=E_1^2 G_{11}+E_1E_2 Y_{12} \cos (\delta_{12} - \theta_{12})$; where P_e^1 is the output power of the generators, G_{11} is the self conductance of bus 1, Y_{12} is the transfer admittance between buses 1 and 2, δ_{12} is the angular displacement of the rotor of machine 1 with respect to another machine or a bus (infinite or not) θ_{12} is equal $\tan^{-1} X_{12}/R_{12}$; where X_{12} is the reactance between buses 1 & 2 and R,sub.12 is the resistance,
$P_c^1=E_1^2G_{11}$, $P_{max} = E_1.E_2/X_{12}$
K=(180 f/H) (Δ t)², which is a machine and a study constant. After fault clearing, P_e^1, P_c^1, P_{max}, are also calculated. For each of the two conditions the following is calculated: P_m- P_c, P_{max} and γ; where γ = θ -90. During fault, the pertinent values are substituted in the following equations and after clearing those corresponding to the condition are substituted:

Step 1: $RTR_1 = \delta -(\theta -90)$, $PMA_1 = P_{max} \sin (RTR_1)$
$PA_1 = P_m-P_c-PMA_1$, $MPA_1=K(PA_1)$,
$\Delta \delta_1=KPA_1$, $\delta_1=\Delta \delta_1 + \delta_o$

Step 2: $RTR_2 = \delta$,sub>1-(θ - 90), $PMA_2 = P_{max} \sin (RTR_2)$
$PA_2 = P_m-P_c-PMA_2$, $\Delta \delta_2=\Delta \delta_1+K(PA_2)$,
$\delta_2=\Delta \delta_2+\delta_1$,...and so on, from which a table .05 and its corresponding angle is built (i.e. .05 and its corresponding δ_1, .1 and δ_2, .15 and δ_3,...and so on)
There is one special case which is the time of clearing will be equal to the time interval of the study (selected) or multiple thereof. Under such condition, the following equations are used (at the instant of clearing, the average value of PA (accelerating power) during and post clearing fault, is calculated:

$RTR_{n+1} = \delta_n-(\theta -90)$

$PMA_{n+1} = P_{max} \sin (RTR_{n+1})$
$PA_{n+1} = P_m - P_c - P_{max} \sin (RTR_{n+1})$

the above equations are calculated using the during fault values of θ, P_{max}, P_m and P_c, the same are calculated using the after clearing values and the average accelerating power (PA_{av}) will be equal to $[PA|_{during\ fault} + PA|_{post}]/2$, $\Delta\delta_{n+1} = \Delta\delta_n + K\,(PA_{av})$, $\delta_{n+1} = \delta_n + \Delta\delta_{n+1}$. For a typical system that may require a study into its stability conditions, click here.
Complete example program in Quickbasic.

Contents

CHAPTER 8
ELECTRICAL POWER DISTRIBUTION MANAGEMENT INFORMATION SYSTEMS (EPDMIS)

I- The model of EPDMIS given in this book divides the major components and equipment found in power distribution systems into seven main categories and each category has its own subclassifications. The headings of the seven categories (essential data tables) are:

-Constants of power systems elements which can be subclassified into: reliability data; typical reactance values for induction and synchronous machines; resistance and reactance of copper and aluminum conductors, reactance spacing factors, reactance of typical 3 phase cable circuits, typical ranges of X/R ratios of transformers, squirrel cage induction motors and synchronous machines; transformers winding, outdoor bushing, phase bus, generator armature and instrument transformers typical capacitance values, impedance of distribution and power transformers; the inertia constant H of the different types of synchronous machines.

-Switchgear and circuit breakers data which can be further subclassified into: typical low and medium voltage circuit breakers ratings; typical ranges for control voltage/current and operating times of m.v.c.b.s; approximate weights of l.v. and m.v. circuit breakers and enclosures; overall dimensions of m.v. and l.v. switchgear cubicles; maximum temperature rise for switchgear assemblies components; minimum spacings for control, l.v. and m.v. circuits; dielectric strength, impulse and corona (partial discharge) testing of m.v. switchgear assemblies; typical metering and relaying accuracies for l.v. and m.v. instrument transformers; burden and accuracy limits for metering instrument transformers; dielectric test values and temperature limits of instrument transformers; definitions of potential (voltage) transformer groups.

-Cables data up to 46KV which includes: allowable ampacities and correction factors for buried and in air cables; properties of teck, EPR jacketed or unjacketed, XLPE jacketed or unjacketed cables; properties of l.v. cables; general properties of XLPE, PVC and EPR.

-Overhead and underground distribution equipment which can further be classified into: typical dimensions for pole mounted, dry, liquid filled, padmounted (radial and loop) transformers; ratings and test values for distribution transformers, wooden poles and concrete poles data; oil switches, air and SF6 switches data; sectionalizes and reclosers data; air insulated, oil insulated, vacuum/SF6 padmounted switchgear specifications; typical lightning arresters ratings.

-Conductors, steel and bus works data including conductors general information: tensile properties of hard drawn and medium hard drawn copper; elongation properties of soft or annealed copper; construction details of copper, compact copper, aluminum steel reinforced (ACSR), aluminum stranded, self damping and compact ACSR, aluminum alloy standard(AASC) conductors; thickness of steel gauges; densities of different varieties of iron and steel; weight and thickness of galvanized steel; hardness of carbon and galvanized steel; mechanical properties of common grades of constructional and stainless steel; composition of some grades of steel; current carrying capacity of bus bars; general properties of bus bars.

-u>Instruments, meters and relays would include: a.c. switchboard instruments burden and other ratings; watt hour, VAR and solid state meters data; distance, differential, overcurrent, overvoltage/undervoltage, synchro check/synchronizing, phase sequence, phase unbalanced, current, negative sequence time overcurrent, reverse power directional, loss of excitation, directional, reclosing,

frequency, motor protection and feeder protection relays data.
-Motors and contactors which can further be classified into: electric motors general information; frame sizes for design B induction motors; typical weights and dimensions of S.C.I.M.; efficiency designation of motors; insulation materials classification for motors windings; electrical ratings for l.v. magnetic contactors/starters, full voltage (FV) l.v. combination starter units, FVLV 2-speed starter units (constant or variable torque); FVLV 2-speed starter units (constant HP) and reduced voltage low voltage starter units; adjustments of magnetic (only) trip element circuit breakers; typical fuse sizes for motor short circuit protection; power factor correction capacitors for l.v. motor controllers; m.v. contactors ratings; dimensions and weights of m.v. controllers; m.v. fuse characteristics for m.v. motor controllers, typical sizes of exciters for synchronous motors. A sample program in Quickbasic.

Contents