بسم الله الرحمن الرحيم

University of Khartoum

Faculty of Engineering & Architecture

Electrical Department

Studying of Impulse Voltage Generator Circuits

Athesis submitted for partial of requirements for the degree of master in elctric power engineering

Submitted by:

Montassir Mohammed Abdulgadir Alhaddad

supervised by:

Prof : Alamin Hamuda

CONTENTS

بسم ا   الرحمن الرحيم

ا   نور السموات والارض مثل نوره كمشكاة فيها مصباح المصباح فـى زجاجة الزجاجة كأنها كوكب درى يوقد من شجرة مباركـة زيتونـة لا شرقية ولا غربية يكاد زيتها يضيئ ولو لم تمسسه نار نور علـى نـور يهدى ا   لنوره من يشاء ويضرب ا   الامثال للناس وا   بكل شئ عليم .

صدق ا   العظيم

الاهداء

الى الوالدة العزيزه

الى الوالد العزيز

الى الاخوه الاعزاء

الى اخى الغائب عبد القادر

الى كل مهتم بهذا المجال

منتصر

Dedication

This work is dedicated to my mother.... Father . . . Brothers . . . absent brother Abdul Gadir … Friends… … and also to every one who is interested in this field.

Acknowledgement

First of all, I would like to thank Allah for this continuous blessing, which make this work is neither the first nor the last. I would like to convey my deepest gratitude to my supervisor, Dr. Alamin Hamuda, for his guidance assistance.

Finally I would like to express my gratitude to every one who has contributed to the completion of this work.

Objective

It is essential for electrical power engineers to reduce the number of outages and preserve the continuity of service and electric supply. Therefore, it is necessary to direct special attention towards the protection of transmission lines and power apparatus from the chief cause of over voltages due to lightning and switching, so it becomes necessary to simulate these transient voltages for laboratory testing purposes. These tests together ensure capability of an apparatus.

There are two types of impulse voltage generator circuits.

1/ Single – stage Generator Circuits

In these circuits the capacitor C_1 is slowly charged from a d.c. source until the spark gap breaks down. The resistors R_1 and R_2 and the capacitor C_2 or other combination form the wave-shaping network.

2/ Multi - stage Generator Circuits (Marx circuit):

The Multi-stage generator uses capacitors charged in parallel and then discharged in series.

The differential equations of the single–stage circuits and a two – stage Marx circuit have been obtained, hence the block diagrams of these circuits have been derived by using integrators, gains and sums from which Matlab programs were written to simulate the wave shape form.

The result shows that:

1. The effect of inductance is to cause oscillation on the wave shape.
2. If the series resistance R_1 is increased, the wave front oscillation is damped, but the peak value of the voltage is reduced.
3. The magnitude of the out put voltages of the tow-stage generator circuit is greater than the single-stage.

الخلاصة

من ابرز اهتمامات المهندس الكهربائى هى تقليل عملية خروج المعدات الكهربائية مـن العمل وضمان استمراريتها لذلك انصب الاهتمام فى حماية خطوط النقل و المحطات الفرعيـة من الارتفاع المفاجئ فى الجهد بسبب الصواعق وعملية القفل والفتح. فكان مـن الـضرورى محاكاة هذا الجهد العابر والمتغير لاستخدامه فى اختبارات الضغط العالى لمعرفة مدى تحمـل العوازل لهذه الهزات ومن هنا جاءت اهمية دراسة الدوائر المولدة للجهد الدفعى.

هنالك نوعين من الدوائر المولدة للجهد الدفعى :

1/ الدائرة المولدة ذات المرحلة الواحدة: فى هذه الدوائر يتم شـحن المكثـف الاول C_1 مـن مصدر للجهد المستمرحتى تعمل ثغرة الشرارة. المقاومتان R_1, R_2 والمكثـف C_2 أو بعـض العناصرالاخرى تشكل بقية مكونات الدائرة.

2/ الدائرة المولدة ذات المراحل المتعددة: وهى دائرة تحتوى على عدة مكثفات يتم شحنها على التوازى وتفريغها على التوالى .

تم استخراج المعادلات التفاضلية للدوائرا لمولدة ذات المرحلة الواحدة ودائرة واحده لمولد ذو مرحلة ثنائية . حيث تم رسم الشكل التخطيطى الاطارى بواسطة مكامل وكسب و مجمع ومن ثم كتابة برامج بلغة Matlab لرسم منحنى الجهد الخارجى.

وكانت النتائج تتلخص فى الاتى:

- المحاثة تحدث تأرجح فى منحنى الجهد.

2. بزيادة مقاومة التوالى يمكن تخميد هذا التأرجح ولكن القيمة العظمى للجهد تتناقص بزيادة المقاومة.

3.القيمة العظى للجهد المولد بواسطة المولد ذو المرحلة الثنائية اكبر من جهد المولد ذو المرحلة الواحدة.

Chapter One

<u>Introduction</u>

Disturbances of electric power transmission and distribution system are frequently caused by tow kinds of transient voltages whose amplitude may greatly exceed the peak values of normal A.C. voltage.

The first kind is lightning over voltage, originated by lightning strokes hitting the phase wires of overhead lines or the busbar of outdoor stations. The amplitudes are very high, usually in the order of 1000kv or more, depending upon the insulation. Exhaustive measurement and long experience have shown that lightning over voltages are characterized by short front duration, ranging from a fraction of micro second to several tens of microseconds and then slowly decreasing to zero.

The second kind is caused by switching phenomena. Their amplitudes are always related to the operating voltage and the shape is influenced by the impedance of the system as well as by the switching condition .The rate of voltage rise is usually slower, but it is known that the wave shape can also be very dangerous to different insulation systems.

Though the actual shape of both kinds of over voltages varies strongly, it became necessary to simulate these transient voltages by relatively simple means for testing purposes. Today the various national and international standards define the impulse voltage as a unidirectional voltage which rises rapidly to a peak value and then decays relatively slowly to zero.

The impulse testing is necessary to ensure that the electrical equipment is capable of withstanding the over voltages that are met within service and to ensure a reliable service for system build by this tested equipment.

The impulse voltage can be generated by:

1. Single-stage impulse generators
2. Multi-stage impulse generators

The basic circuits for single-stage impulse generators are shown in Fig.4.3 .The capacitor C_1 is slowly charged from a D.C. source until the spark gap breakdown. This spark gap acts as a voltage-limiting and voltage-sensitive switch. The resistors R_1 and R_2 and the capacitance C_2 form the wave-shaping network. R_1 will primarily damp the circuit and control the front time. R_2 will discharge the capacitors and therefore essentially control the wave tail.

A multistage impulse generator requires several component parts for flexibility and for production of the required wave shape. This may be grouped as d.c. charging set, charging resistors generator capacitors, spark gaps, wave-shaping resistors and capacitors, triggering system and voltage divider.

The multi-stage generator uses capacitors charged in parallel. These capacitors are then discharged in series to achieve higher voltage from a relatively low voltage source. The capacitors are discharged by use of spheres, which act as switches. This design was credited by Marx 1924. As a result; the multi-stage generator is commonly referred to as a Marx generator. All capacitors, one in each stage, are charged to a voltage V relative to ground. The bottom sphere gap is triggered by voltage injection and breakdown, discharging that stage capacitor. Subsequently, the remaining stage gaps also breakdown, discharging each stage capacitor. The result is accumulative swing in voltage from zero to nV, where n is the number of stages.

Chapter Two

Lightning over voltages and switching over voltages

Lightning phenomenon is a peak discharge in which charge accumulated in the clouds discharges into a neighbouring cloud or to the ground. The electrode separation, i.e. cloud to cloud or cloud to ground is very large, perhaps 10 Km or more. Lightning strikes to overhead transmission cause traveling waves which propagate along the overhead line and enter substations where they cause over voltages which can pose a risk to any items of equipment connected, such as cables or transformers.

2.1 Types of lightning stresses

(a) Remote strikes

Remote strikes are those that are not occur in the immediate vicinity of the switchgear. These remote strikes result in traveling waves which are simulated by a lightning impulse voltage with a front time of 1.2 ms and a time to half-value of 50 ms.The traveling waves propagate towards the switchgear, and it is assumed that the amplitudes occurring are below the flashover voltage of the insulator of the overhead power transmission line. Therefore, remote strikes do not lead to any flashovers at the overhead line insulators in the immediate vicinity of the switchgear.

(b) Strikes to towers

Lightning strikes which directly strike towers increase the potential of towers affected and can, dependant on the level of the tower footing resistance and the electric strength of the overhead lines insulators, lead to backward flashovers cause traveling waves which propagate via the overhead line toward the switchgear.

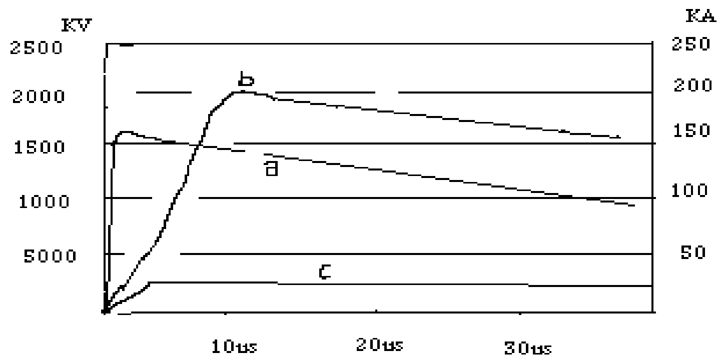


Fig.2.1 Simulation of lightning currents and voltages

(c) Nearby direct strike to overhead lines conductors

The current amplitudes of the lightning strikes which strike an overhead line conductor are influenced very considerably by the tower geometry and the shielding effect of the overhead wires. High towers with wide conductor spacing and considerable angles of protection from the overhead earth wires lead to higher lightning strike currents in the event of the direct strikes to the overhead line conductor. Thus, the amplitude of the lightning strike currents is therefore calculated as a function of the tower geometry for overhead transmission lines. Usually, the lightning strike currents are within arrange of approximately 10KA to 60KA.

2.2 Origin of switching surge

The making and breaking of electric circuits with switchgear may result in abnormal over voltages in power systems having large inductances and capacitances. The over voltages may go as high as six times the normal power frequency voltages. In circuit breaking operation, switching surges with a high rate of rise of voltage may cause repeated restriking of the arc between the contacts of the circuit breaker, thereby causing destruction of the circuit breaker contacts. The switching surges may include high natural frequencies of the system, a damped normal frequency voltage component, or the restriking and recovery voltage of the system with successive reflected waves from termination.

2.2.1 Characteristics of switching surges

The wave shapes of switching surges are quite different and may have origin from any of the following sources:

(i) De energizing of transmission lines, cables, shunt capacitors, etc.

(ii) Disconnection of unloaded transformers, reactor, etc.

(iii) Energizing or reclosing of lines and reactive loads.

(iv) Sudden switching off of load.

(v) Short circuits and fault clearance

Typical wave shapes of the switching surges are given in Fig.2.2. From the figures of the switching surges it is clear that the over voltages are irregular (oscillatory or unipolar) and can be of high frequency or power frequency with its harmonics. The relative magnitudes of the over voltages may be about 2.4 p.u. in the case of transformer energizing and 1.4 to 2.0 p.u. in switching transmission lines.

2.2.2 Power Frequency over voltages in power system

The power frequency over voltages occurs in large power systems and they are of much concern in EHV systems, i.e. systems of 400 KV and above. The main Cause for power frequency and its harmonic over voltages are

(a) Sudden loss of loads.

(b) Disconnection of inductive loads or connection of capacitive load.

(c) Unsymmetrical faults.

(d) Saturation in transformers, etc.

2.2.3 Control of over voltages due to switching

The over voltages due to switching at power frequency may be controlled by

(a) Energizing of transmission lines in one or more steps by inserting resistances and withdrawing them afterwards.

(b) Phase controlled closing of circuit breaker.

(c) Drainage of trapped charges before reclosing.

(d) Use of shunt reactor.

(e) Limiting switching surges by suitable surge diverters.

(a) Insertion of resistors

It is normal and common practice to insert resistances R in series with circuit breaker contacts when switching on but short circuiting them after a few cycles. This will reduce the transients occurring due to switching. The voltage step applied is first reduced to $Z_O/(R+Z_O)$per unit where Z_O is the surge impedance of the line. It is reflected from the far end unchanged and again reflected back from the near end with reflection factor $(R-Z_O)/(R+Z_O)$per unit. If$R=Z_O$, there is no reflection from the far end. The applied step at the first instance is only 0.5 per unit. When the resistor is short circuited, a voltage step equal to the instantaneous voltage drop enters the line. If the resistor is kept for a duration larger than 5 ms (for 50 Hz sine wave =1/4 cycle duration), it can be shown from successive reflections and transmissions, that the over voltage may reach as high as 1.2p.u. for a line length of 500 Km.But for conventional opening of the breaker, the resistors have too high an ohmic value to be effective for resistance closing. Therefore, pre-insertion of suitable value resistors in practice is done to limit the over voltage to less than 2.0 to 2.5 p.u. Normal time of insertion is 6 to 10 m s.

(b) Phase controlled switching

Over voltages can be avoided by controlling the exact instances of the closing of the three phases separately. But this necessitates the use of complicated controlling equipment and therefore is not adopted.

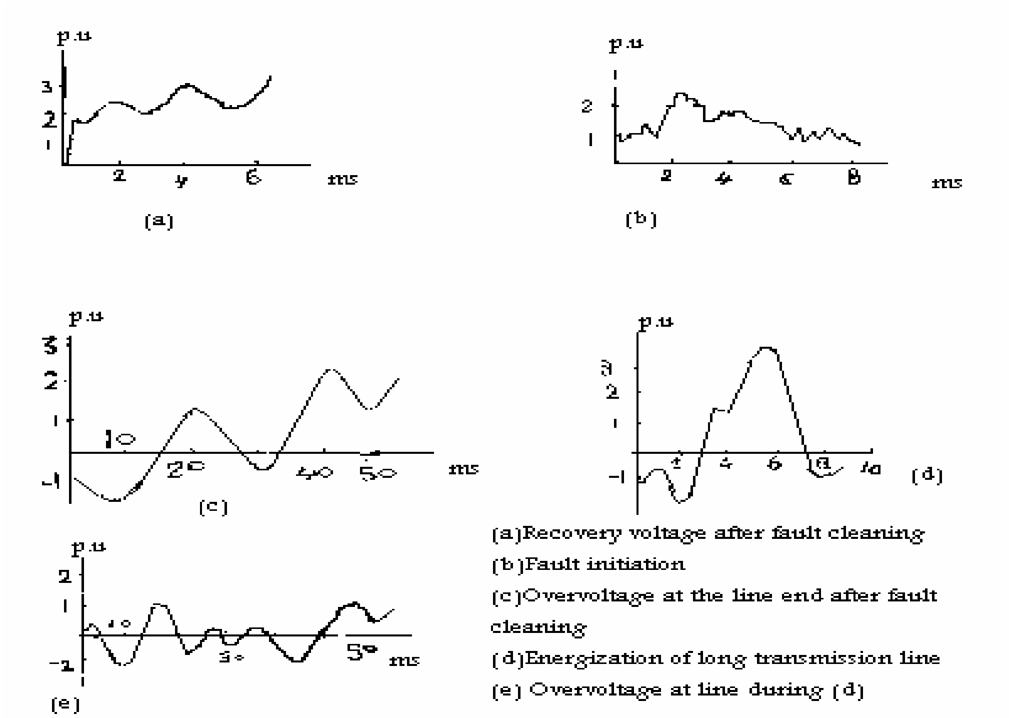


Fig.2.2 Typical waveshape of switching surge voltages

(c) Drainage of Trapped Charged

When lines are suddenly switching off, electric charge may be left on capacitors and line conductors. This charge will normally leak through the leakage path of insulators, etc. Conventional potential transformers (magnetic) may also help the drainage of the charge. An effective way to reduce the trapped charges during the dead time before reclosing is by temporary insertion of resistors to ground or in series with shunt reactors and removing them before the closure of the switches.

(d) Shunt Reactor

Normally all EHV lines will have shunt reactors to limit the voltage rise. They also help in reducing surges caused due to sudden energizing. However, shunt reactors cannot drain the trapped charge but will give rise to oscillations with the capacitance of the system. Since the compensation given by the reactors will be less than 100%, the frequency of oscillation will be less than the power frequency, and over voltage produced may be as high as 1.2 p.u. Resistors in series with these reactors will suppress the oscillations and limit the over voltages.

2.3 Protection against lightning over voltages and switching surges of short duration

Protection of transmission lines against natural or lightning over voltages and minimizing the lightning over voltages are done by suitable line design, providing quard and ground wires, and using surge diverters. Switching surges and power frequency over voltages are accounted for by providing greater insulation levels and with proper insulation levels and with proper insulation coordination.

Over voltages due to lightning strokes can be a voided or minimized in practice by:

(a) Lightning Protection using Shielded Wires or Ground Wires

Ground wire is a conductor run parallel to the main conductor of the transmission line supported on the same tower and earthed at every equally and regularly spaced towers. It is run above the main conductor of the line. The ground wire shields the transmission line conductor from induced charges, from clouds as well as from alighting discharge.

The mechanism by which the line is protected may be explained as follows. If a positively charged cloud is assumed to be above the line, it induces a negative charge on the portion below it, of the transmission line. With the ground wire present, both the ground wire and the line conductor get the induced charge. But the ground wire is earthed at regular intervals, and as such the induced charge is drained to the earth potential only; the potential difference between the ground wires and the clouds and that between the ground wires and the transmission line wire will be in the inverse ratio of their respective capacitances (assuming the cloud to be a perfect conductor and the atmospheric medium (air) a dielectric). As the ground wire is nearer to the line wire, the induced charge on it will be much less and hence the potential rise will be quite small. The effective protection or shielding given by the ground wire depend on the height of the ground wire above the ground (h) and the protection or shielding angles θ_s (usually 30) as shown in Fig.2.3.

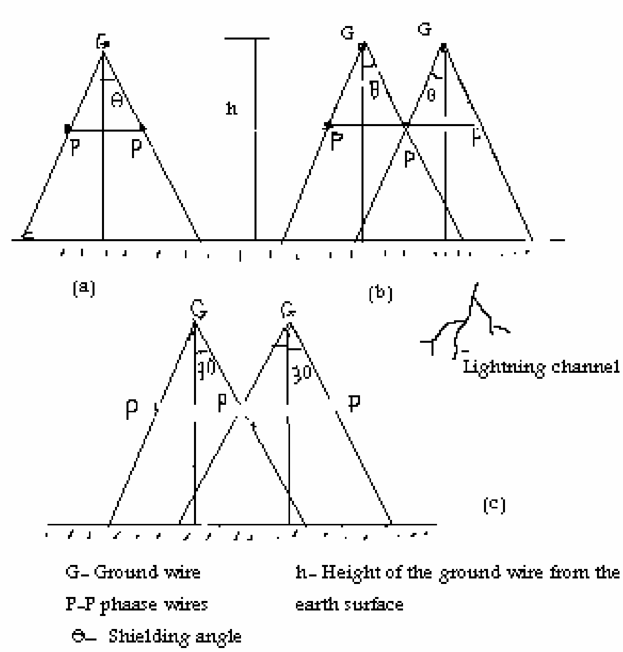


Fig.2.3 Shielding arrangement of overhead lines by ground wires

(b) Protection using Ground Rods and Counter-Poise Wire

When a line is shielded, the lightning strikes either the tower or the ground wire, the path for drainage of the charge and lightning current is (a) through the tower frame to ground, (b) through the ground line in opposite directions from the point of striking. Thus the ground wire reduces the instantaneous potential to which tower top can rise is

$$V_T = I_O.Z_T /(1 + Z_T / Z_S)$$

Where, Z_T = surge impedance of the tower, and

Z_S = surge impedance of the ground wire.

If the surge impedance of the tower, which is the effective tower footing resistance, is reduced, the surge voltage developed is also reduced considerably. This is accomplished by providing driven ground rods and counter-poise wires connected to tower legs at the tower foundation. Ground rods are a number of rods about 15 mm diameter and 2.5 to 3 m long driven into the ground. In hard soils the rods may be much longer and can be driven to a depth of, say, 50 m. They are usually made of galvanized iron or copper bearing steel. The spacing of the rods, the number of rods, and the depth to which they are driven depend on the desired tower footing resistance. With 10 rods of 4 m long and spaced 4 m apart, connected to the legs of the tower, the dynamic or effective resistance may be reduced to 10 ohms.

The above effect is alternatively achieved by using counter-poise wires. Counter-poise wires are wires buried in the ground at a depth of 0.5 to 1.0 m, running parallel to the transmission line conductors and connected to the tower legs.

(c) Protective Devices

In regions where lightning strokes are intensive or heavy, the overhead lines within these zones are fitted with shunt protected devices. On the line itself two devices known as expulsion gaps and protector tubes are used. Line terminations, junctions of lines, and sub-stations are usually fitted with surge diverters.

(i) Expulsion gaps

Expulsion gap is a device which consists of a spark gap together with an arc quenching device which extinguishes the current arc when the gaps break over due to over voltages. It essentially consists of a rod gap in air in series with a second gap enclosed within a fibre tube. In the event of an over voltage, both the spark gaps breakdown simultaneously. The current due to the over voltages is limited only by the tower footing resistance and the surge impedance of the ground wires. The internal arc in the fibre tube due to lightning current vaporizes a small portion of the fibre material. The gas thus produces, being a mixture of water vapour and the decomposed fibre product, derives away the arc products and ionized air. When the follow-on power frequency current passes through zero value, the arc is extinguished and the path becomes open circuited. Meanwhile the insulation recovers its dielectric strength, and the normal conditions are established. The lightning and follow-up power frequency currents together can last for 2 to 3 half cycles only. Therefore, generally no disturbances in the network are produced.

(ii)Protective Tubes

A protective tube is similar to the expulsion gap in, construction and principle. It also consists of a rod or spark gap in air formed by the line conductor and its high voltage terminal. The hollow gap in the expulsion tube is replaced by a nonlinear element which offers very high impedance at low currents but has low impedance for high or lightning currents. When an over voltages occur and the spark gaps break down, the current is limited both by its own resistance and the tower footing resistance. The over voltages on the line is reduced to the voltage drop across the protector tube. After the surge current is diverted and discharged to the ground, the follow-on normal power frequency current will be limited by its high resistance. After the current zero of power frequency, the spark gap recovers the insulation strength quickly. Usually, the flashover voltage of the protector tube is less than that of the line insulation, and hence it can discharge the lightning over voltage effectively.

(iii) Surge diverter or lightning arrestor

Surge diverters or lightning arresters are devices used at sub-station and at line transmission to discharge the lightning over voltages and short duration switching surges. These are usually mounted at the line end at the nearest point to the sub-station. They have a flash over voltage lower than that of any other insulation or apparatus at the sub-station.

The ideal requirements of a protective device connected in parallel or in shunt are:

(a) It should not usually flash over for power frequency over voltages.

(b) The volt-time characteristics of the device must lie below the withstand voltage of the protected apparatus or insulation.

(c) It should be capable of discharging high energies contained in surges and recover insulation strength quickly.

(d) It should not allow power frequency follow-on current to follow.

Chapter three

Impulse voltage laboratory tests

Industrial and economic development in the present world demands the use of more and more electrical energy which has to be transported over long distance in large quantities. Transportation of large amount of power needs extra high voltage transmission lines.

This very fast development of power systems should be followed by system studies on equipment and service conditions which they have to fulfill. These conditions will also determine the values for test voltages of a .c. power frequency, impulse, or d.c., under specific conditions.

High voltage laboratories are an essential requirement for making acceptance tests for the equipment that go into operation in the extra high voltage transmission system. In addition, they are also used in the development work on equipment for conducting research, and for planning to ensure economical and reliable extra high voltage transmission systems.

A high voltage laboratory is expected to carry out withstand and / or flashover tests at high voltages on the following transmission system equipment:

(i) Transformers

(ii) Lightning arrestor

(iii) Isolator and circuit breakers

(iv) Different types of insulators

(v) Cables

(vi) Capacitors

(vii) Line hard ware and accessories

(viii) Other equipment like reactors, etc.

Different tests conducted on the above equipment are:

(i) Power frequency withstand test - wet and dry

(ii) Impulse tests

(iii) D.C. withstand tests

(iv) Switching surge tests

(v) Tests under polluted atmospheric conditions

High voltage laboratories, in addition to conducting tests on equipment, are used for research and development works on the equipment. This includes determination of the safety factor for dielectrics and reliability studies under different atmospheric conditions such as rain, fog, industrial pollution, etc., at voltage higher than the test voltage required.

Research activities usually include the following:

(i) Breakdown phenomenon in insulating media such as gases, liquids, solids, or composite systems.

(ii) Withstand voltages on long gabs, surface flashover studies on equipment with special reference to the equipment and materials used in power systems.

(iv) Studies on insulation coordination on H. V. power, usually high voltage laboratories involve tremendous cost. Hence, planning and layout have to be carefully done so that with the testing equipment chosen, the investment is not too high and the maximum utility of the laboratory is made.

3.1 Breakdown of solid, liquid and gas:-

Modern high voltage test laboratories employ voltage up to 6 MV or more. The diverse conditions under which a high voltage apparatus is used necessitate careful design of its insulation and the electrostatic field profiles. The principal media of insulation used are gases, vacuum, solid and liquid, or a combination of these.

In high voltage applications, the dielectric strength of insulating materials and the electric field stresses developed in them when subjected to high voltage are the important factors in high voltage systems. In high voltage apparatus the important materials used are conductors and insulators. While the conductors carry the current, the insulators prevent the flow of currents in undesired paths.

As already mentioned, the most important material used in a high voltage apparatus is the insulation. The dielectric strength of an insulating material can be defined as the maximum stress which the material can withstand. It can also be defined as the voltage at which the current start increasing to very high values unless controlled by external impedance of the circuit. The electric breakdown strength of insulating material depend on a variety of parameters, such as pressure, temperature, humidity , field configurations , material of electrodes , and surface conditions of electrodes, etc . An understanding of the failure of the insulation will be possible by the study of the possible mechanisms by which the failure can occur.

The most common cause of insulation failure is the presence of discharge either within the voids in the insulation or over the surface of the insulation. The probability of failure will be greatly reduced if such discharges could be eliminated at the normal working voltage. Then, failure can occur as a result of thermal or electrochemical.

The breakdown of air is of considerable practical importance to the design engineers of power transmission lines and power apparatus. Breakdown occurs in gases due to the process of collisional ionization, electrons get multiplied in an exponential manner, and if the applied voltage is sufficiently large, breakdown occurs. In some gases, free electrons are removed by an attachment to neutral gas molecules; the breakdown strength of such gases is substantially large. An example of such a gas with large dielectric strength is sulphur hexafluoride (SF_6).

The breakdown strength of gases increases steadily with the gap distance between electrodes; but the breakdown voltage gradient reduces from 3 MV/m for uniform fields and small distances to about 0.6 MV/m for large gaps of several meters. For very large gaps as in lighting, the average gradient reduces to (0.1 - 0.3) MV /m.

Liquids are used in high voltage equipment to serve the dual purpose of insulation and heat conduction. They have the advantage that a puncture path is self-healing. Temporary failures due to over voltages are reinsulated quickly by liquid flow to the attacked area. However, the products of the discharges may deposit on solid insulation supports and may lead to surface breakdown over these solid supports.

Highly purified liquids have dielectric strengths as high as IMV/cm. Under actual service conditions, the breakdown strength reduces considerably due to the presence of impurities. The breakdown mechanism in the case of very pure liquid is the same as the gas breakdown, but in commercial liquids, the breakdown mechanisms are significantly altered by the presence of the solid impurities and dissolved gases.

If the solid insulating material is truly homogeneous and is free from imperfections, its breakdown stress will be as high as 10 MV/ cm. This is the “intrinsic breakdown strength”, and can be obtained only under carefully controlled laboratory conditions. However, in practice, the breakdown fields obtained are very much lower than this value. The breakdown occurs due to many mechanisms. In general, the breakdown occurs over the surface, than in the solid itself, and the surface insulation failure is the most frequent cause of trouble in practice.

The breakdown of insulation can occur due to chemical failure caused by the mechanical stresses produced by the electrical field. This is called “electromechanical” breakdown.

On the other hand, breakdown can also occur due to chemical degradation caused by the heat generated due to dielectric losses in the insulating material. This process is cumulative and is more severe in the presence of air and moisture.

3.2 Impulse testing of Insulator

(a) Impulse withstand voltage test

This test is done by applying the standard impulse voltage of specified value under dry conditions with both positive and negative polarities of the wave. If five consecutive waves do not cause flashover or puncture, the insulator is deemed to have passed the test. If two applications cause flashover, the object is deemed to have failed. If there is only one failure, additional ten application of the voltage wave are made. If the test object has withstood the subsequent applications, it is said to have passed the test.

(b) Impulse flashover test

The test is done as above with the specified voltage. Usually, the Probability of failure is determined for 40% and 60% failure values or 20% and 80% failure values, since it is difficult to adjust the test voltage for the exact 50% flashover values. The average value of the upper and the lower limit is taken. The insulator surface should not be damaged by these tests, but slight marking on its surface or chipping off of the cement is allowed.

(c) **Pollution Testing**

Because of the problem of pollution of outdoor electrical insulation and consequent problems of the maintenance of electrical power systems, pollution testing is gaining importance. The normal types of pollution are (i) dust, micro – organism, bird secretions, flies, etc.

(ii) Industrial pollution like smoke, petroleum vapours, dust, and other deposits,
(iii) Coastal pollution in which corrosive and hygroscopic salt layers are deposited on the insulator surfaces,
(iv)Desert pollution in which sand storm cause deposition of sand and dust layers,
(v) Ice and fog deposits at high altitudes and in polar countries.

These pollutions cause corrosion, non-uniform gradients along the insulator strings and surface of insulators and also cause deterioration of the material. Also, pollution causes partial discharges and radio interference. Hence, pollution testing is important for extra high voltage systems.

At present there is no standard pollution test available. The popular test that is normally done is the salt fog test. In this test, the maximum normal withstand voltage is applied on the insulator and then artificial salt fog is created around the insulator by jots of salt water and compressed air. If the flashover occurs within one hour, the test is repeated with fog of lower salinity, otherwise, with a fog of higher salinity. The maximum salinity at which the insulator withstands three out of four tests without flashover is taken as the representative figure. Much work is yet to be done to standardize the test procedures.

3.3 Impulse testing of Bushing

(a) Full wave withstand test

The bushing is tested for either polarity voltages as per the specifications. Five consecutive full waves of standard waveform are applied, and if two of them cause flashover, the bushing is said to have failed in the test. If only one flashover occurs, ten additional applications are done. The bushing is considered to have passed the test if no flashover occurs in subsequent applications.

(b) Under - oil flashover / withstand test

This test is done with 15% higher voltages impulse wave applied than for full wave withstand test .Two consecutive impulse voltages of either polarity are applied. While flashover in air is allowed, no internal failure or under-oil flashover should occur.

(c) Chopped Wave Withstand and Switching Surge Tests

The chopped wave test is sometimes done for high voltage bushings (220kv and 400kv and above). Switching surge flashover test of specified values is nowadays included for high voltage bushings. The tests are carried out similar to full wave withstand tests.

3.4 Impulse testing of transformers.

The purpose of the impulse tests is to determine the ability of the insulation of the transformers to withstand the transient voltages due to lightning, etc. Since the transients are impulses of short rise time, the voltage distribution along the transformer winding will not be uniform. The equivalent circuit of a transformer winding for impulses is shown in Fig.3.1. If an impulse wave is applied to such a network the voltage distribution along the element will be uneven, and oscillation will be set in producing voltages much higher than the applied voltage.

Impulse testing of transformer is done using both the full wave and the chopped wave of the standard impulse, produced by a rod gap with a chopping time of three to six μs .To prevent large over voltages being included in the windings not under test, they are short circuited and connected to ground. But the short circuiting reduces the impedance of the transformer and hence poses problems in adjusting the standard wave shape of the impulse generators. It also reduces the sensitivity of detection.

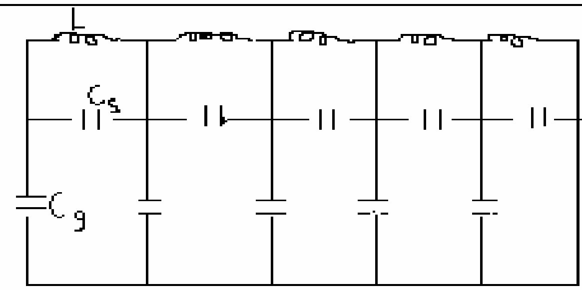


Fig.3.1 Equivalent circuit of transformer winding for impulse

(a) **Procedure for impulse Testing**

The schematic diagram of the transformer connection for impulse testing is shown in fig. 3.2, and the wave shapes of the full and chopped waves are shown in Fig. 3.3. In transformer testing, it is essential to record the waveforms of the applied voltages and current through the windings under test. Sometimes, the transferred voltage in the secondary and the neutral current are also recorded.

Impulse testing is done in the following sequence:

(i) Applying impulse voltage of magnitude 75% of the Basic Impulse Level (BIL) of the transformer under test,

(ii) One full wave voltage of 100% BIL,

(iii) Two chopped waves of 115% BIL.

(iv) One full wave of 100% BIL, and One full wave of 75% BIL.

It is very important to see that the grounding is proper and the windings not under test are suitably terminated.

(b) Detection and location of fault during Impulse Testing

The fault in a transformer insulation is located in impulse tests by any one of the following methods.

(1) General observations

The fault can be located by general observations like noise in the tank or smoke or bubbles in breather.

(2) Voltage oscillogram method

Fault or failure appears as a partial or complete collapse of the applied voltage wave. Figure 3.4 gives the typical waveform. The sensitivity of this method is low and does not detect faults which occur on less than 5% of the winding.

(3) Neutral current method

In the neutral current method, a record of the impulse current flowing through a resistive shunt between the neutral and ground point is used for detecting the fault. The neutral current oscillogram consists of a high frequency oscillation, a low frequency disturbance, and a current rise due to reflections from the ground end of the windings.

When a fault occurs such as arcing between the turns or from turn to the ground, a train of high frequency pulses similar to that in the front of the impulse current wave are observed in the oscillogram and the wave shape changes. If the fault is local, like a partial discharge, only high frequency oscillations are observed without a change of wave shape. The sensitivity of the method decreases, if other windings not under test are grounded.

(4) Transferred surge current method

In this method, the voltage across a resistive shunt connected between the low voltage winding and the ground is used for fault location. A short high frequency discharge oscillation is capacitively transferred at the event of failure and is recorded. Hence, faults at a further distance from the neutral are also clearly located. The wave shape is distorted depending on the location and type of fault, and hence can be more clearly detected.

After the location of the fault, the type of fault can be observed by dismantling the winding and looking for charred insulation or melted parts

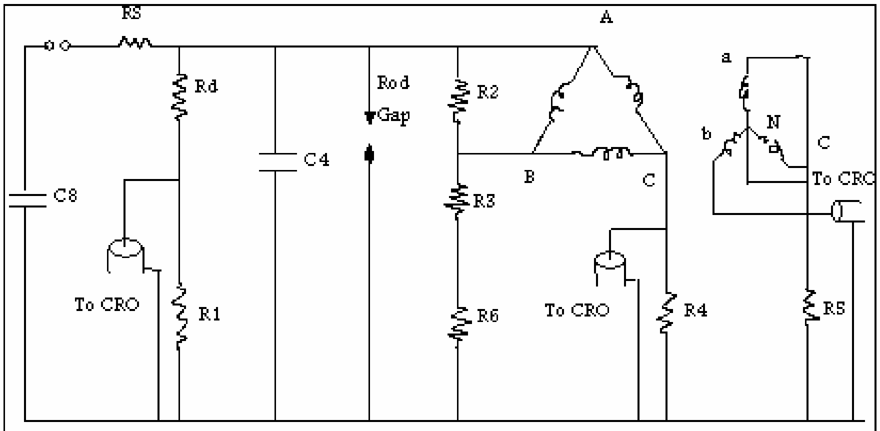


Fig.3.2 Arrangement of transformer for impulse testing

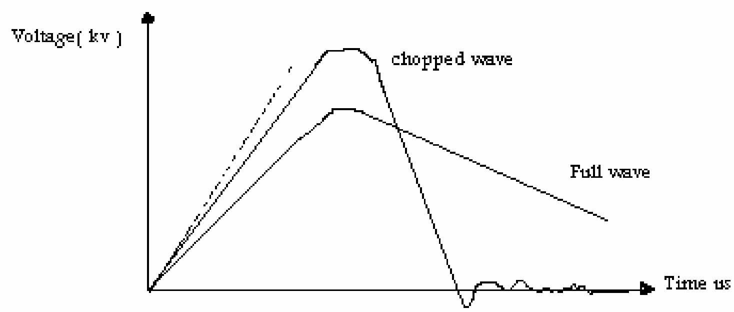
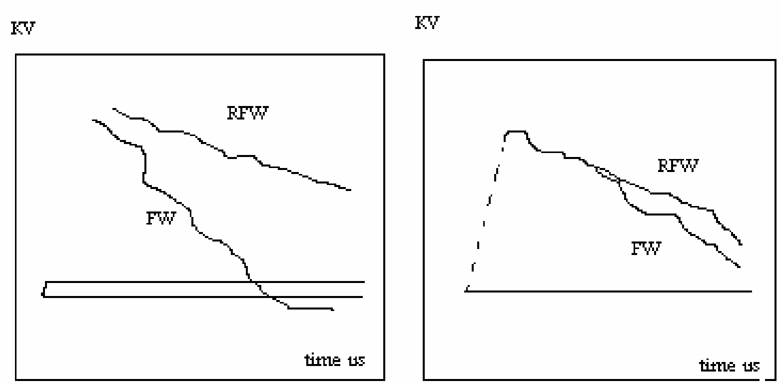


Fig.3.3 Full wave and chopped wave



(a) Failure from line lead to ground through oil

(b)8.5% of winding faile

Fig.3.4 Voltage oscillation of transformer winding with a fault

RFW - Reduced full wave .... FW - full wave on the copper winding. This is successful in the case of major faults. Local faults or partial discharges are self healing and escape observation.

3.5 Impulse testing of surge diverter

1. Hundred percent standard Impulse spark over testing :-

This test is conducted to ensure that the diverter operates positively when over voltages of impulse nature occur. The impulse generator is adjusted to give the standard impulse voltage of a present magnitude specified in the specifications. The arrester has to spark over every time in each of the ten successive applications. The test is done with both positive and negative polarity waveforms. Sometimes, the test is done by starting at a voltage level that does not give flashover at all, and is repeated in increasing steps of voltage till hundred percent flashover occurs. The magnitude of the voltage at which hundred percent flashover occurs is the required spark over voltage.

2. Front of wave spark over test:-

In order to ensure that the surge diverter flashes over for very steep fronted waves of high peaks, this test is conducted using an over voltage having a rate of rise of 100 KV /µs, per 12 KV of the rating. The estimated maximum steepness of the waves is specified in standards and specifications. The test is done by conducting hundred percent sparks over voltage test for increasing magnitude of the standard impulse wave. The time to spark over is measured. The volt- time characteristic of the diverter is plotted, and the intersection of the v-t characteristic and the line with slope of the virtual steepness of the front gives the front of wave spark over voltage.

Chapter Four

Generation of impulse voltage

4.1 Standard impulse Wave shapes

Transient over voltages due to lightning and switching surges cause steep build-up of voltage on transmission lines and other electrical apparatus. These waves have arise time of 0.5 to 10 µs and decay time to 50% of the peak value of the order of 30 to 200 µs. The lightning over voltage wave can be represented by the equation:

$$V = v_0 [\exp(-\alpha t) - \exp(-\beta t)] \qquad (4.1)$$

α and β are constants of microsecond values.

The above equation represents a unidirectional wave, which usually has a rapid rise to the peak value and slowly falls to zero value. The general waves shape is given in Fig.4.1

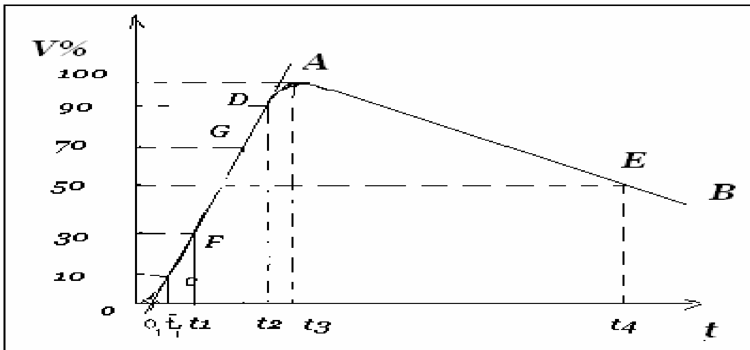


Fig.4.1 Impulse waveform and its definitions

Defining the following specifies impulse waves**:**

The front time:

Referring to the wave shape in Fig. 4.1, the peak value A is fixed and referred to as 100% value. The points corresponding to 10% and 90% of the peak values are located in the front portion (points C and D). The line joining these points is extended to cut the time axis at o_1. O_1 is taken as virtual origin. 1.25 times the interval between times t_1 and t_2 corresponding to points C and D (projections on the time axis) is defined as the front time, i.e. $1.25(o_1 t_2 - o_1 t_1^-)$.

The tail time:

The point E is located on the wave tail corresponding to 50% of the peak value, and its projection on the time axis is t_4. O t_4 is defined as the fall or tail time.

4.2 The general construction of impulse generators

The method of construction of impulse generators is largely governed by the type of capacitors involved. Most of the recently built impulse generators use oil-impregnated capacitors in insolating containers. These capacitors have the dielectric assembled in an insulating cylinder of porcelain or vanished paper with plane metal end-plates .An advantage of this form of capacitors is that successive stages of capacitors can be built up in vertical columns, each stage being separated from the adjacent one by supports of the same form as the capacitors but without the dielectric. Oil-impregnated capacitors in metal tanks are occasionally used, they require an insulating framework and have disadvantage that the voltage for which they are designed is usually low, so that two or more capacitors may have to be connected in series for each stage.

●The wave-front control resistances may be composed of wire, liquid, or solids in the form of pellers or rod .The use of wire may be unsatisfactory because of inductive effects and low heat capacity. Liquid have a high heat capacity but their resistance is unstable.

●The wave-front resistors can be placed out side the generator, partly within and partly outside, or entirely within it. The load and the stray earth capacitance form and oscillatory circuit which needs to be damped by an external resistor. An important practical reason for distributing the wave-front resistors within the generator is that the needs is then diminished for an external resistor capable of withstanding the full voltage.

●Wave-tail control resistances can also perform the function of charging resistances and, in this case, are distributed throughout the generator .However, it is usual to arrange for part of the wave-tail resistance to be placed outside the generator as then it can be used also to serve the purpose of potential divider .With the arrangement, as the wave-tail resistance is on the load side of the wave-front control resistance, there is a loss in the output voltage reaching the load.

●Sphere gaps are made with two metal spheres of identical diameter D with their shanks, operating gear, and insulator support.

Spheres are generally made of copper , brass , or aluminum ,the latter ,is used due to low cost .The standard diameters for the spheres are 2 , 5 , 6.25 , 10 , 12.5 , 15 , 25 , 50 , 75 , 100 , 150 , and 200 cm. The spacing is so designed and chosen such that the flashover occurs near the sparking point. The sphere are carefully designed and fabricated so that their surface are smooth. The surface should be free from dust, grease, or any other coating. The surface should maintained clean but need not be polished. If excessive pitting occurs due to repeated sparkovers, they should be smoothed. It is usual to arrange for the spheres forming the spark gaps to be of such a size that the spacing for the maximum voltage required does not exceed a sphere diameter.

An important consideration is that corona discharge should be absent from the spark gaps, to avoid unnecessary drain on the D.C.set during the charging period, and for this reason sphere gaps with their nearly uniform field distribution are more satisfactory than more asymmetrical forms of gaps.

The setting of the sphere gaps has to be adjusted according to the output voltage required. In the early forms of generators the gaps were adjusted manually, but in the more recent forms of the larger generators it is usual for the gaps to be driven by a remotely controlled motor.

4.3 Circuits for producing impulse waves

A diagram of the discharge circuit of an Impulse generator is given in Fig.4.2 .In many of the practical circuits used some of the elements shown are omitted or are negligible.

A capacitance C_1 is charged from a D.C set to a voltage which cause a discharge through a spark gap into the associated circuit .An Impulse voltage then appears across the resistance R_4 to which the test object is connected.

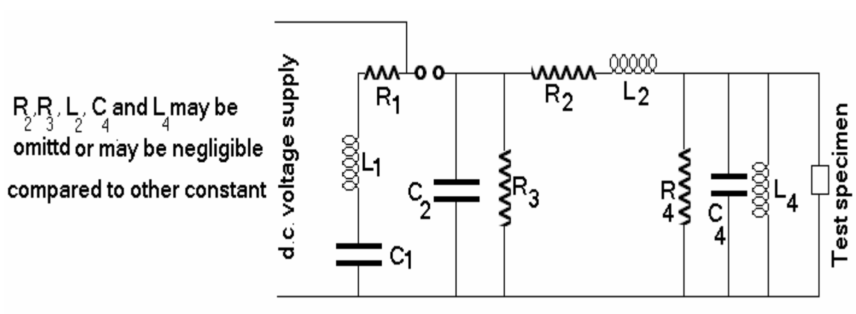


Fig.2.1 Surge generator discharge circiut

The capacitance C_1 may consist of one capacitance , in which case the generator is known as a single–stage generator .The Inductance L_1 depend on the length of the discharge circuit, and is generally kept as small as possible . The resistance R_1 consist of the inherent series resistance of the capacitance and connections, and often includes additional lumped resistances inserted within the generator for damping purposes and for output wave–form control. Additional inductance L_2 and resistance R_2 may be connected at the Generator terminal, again for wave–form control .The function of the resistances R_3 and R_4 is mainly to control the duration of the wave. R_4 can also serve as a potential divider when a cathode –ray oscillograph is used to record the wave –shape .The capacitance C_2 and C_4 represent the capacitances to earth of the high –voltage component and leads .C_4 also includes the capacitance of the test object and of any other load capacitance which may be required for producing the required wave –shape. L4 represent the inductance of the test object and may also affect the wave –shape appreciably.

The impulse characteristics of the test objects may vary widely, and the circuit constants may have to be altered to maintain a specified wave–shape for the impulse voltage developed across the test object .The resistance R_2, R_3 and R_4, The capacitance C_4 and, in some cases, the inductance L_2 should be capable of adjustment.

For practical reason it is usual for one terminal of the Impulse generator to be solidly earthed. The polarity of the impulse voltage is altered by changing the polarity of the output from the D.C.changing set.

Different equivalent circuits that produce Impulse waves are given Figs 4.3 a to d. Circuit shown in Fig.4.3 a is limited to model generators only , and commercial generator employ circuits shown in Figs 4.3 b to 4.3 d .

A capacitor (C_1 or C) previously charged to a particular D.C voltage when suddenly discharged into the wave shaping network (L R,$R_1R_2C_2$ or other combination) by closing the switch S .The discharge voltage $V_0(t)$ shown in Fig 4.3 gives rise to the desired double exponential wave shape.

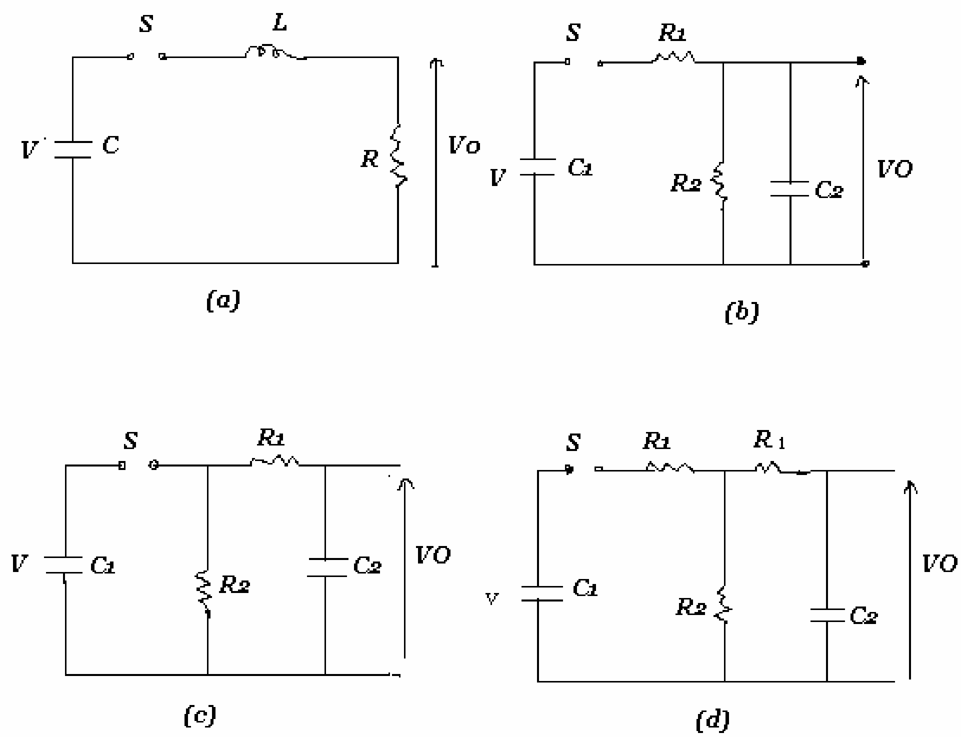


Fig.4.3 Circuits for producing impulse waves

4.4 Multistage Impulse Generators –Marx circuit

Originally described by E. Marx in 1924, Marx Generators are probably the most common way of generating high voltage Impulse for testing when the voltage level required is higher than available charging supply voltages. A single capacitor and its charging unit may be too costly, and the size becomes very large. The cost and size of the impulse generator increases at a rate of the square or cube of the voltage rating. Hence, for producing very high voltages, a bank of capacitors are charged in parallel and then discharged in series.

4.4.1 Components of a multistage Impulse Generator:

For the production of the required wave shape, A multistage Impulse generator requires several component parts .These may be grouped as follows :

(i) D.C charging set:

The charging unit should be capable of giving available d.c Voltage of either polarity to charge the generator capacitors to the required value.

(ii) Charging Resistors:

This will be a non –inductive high value resistor of about 100 Kilo ohms. Each resistor will be designed to have a maximum voltage between 50 and 100 KV.

(iii) Generator capacitors and spark Gaps:

These are arranged vertically one over the other with all the spark gaps aligned .The capacitors are designed for several charging and discharging operations .On dead short circuit, the capacitors will be capable of giving 10 KA of current. The spark gaps will be usually spheres or .hemispheres of 10 to 25 cm diameter. Sometimes spherical ended cylinders with a central support may also be used.

(iv)Wave – shaping Resistors and Capacitors:

Resistors will be non – inductive wound type and should be capable of discharging impulse current of 1000 A or more. Each resistor will be designed for a maximum voltage of 50 to 100 kV. The resistances are bifilar wound or non- inductive thin flat insulating sheets. In some cases, they are wound on thin cylindrical formers and are completely enclosed.

(v) **Triggering System**:

This consists of trigger spark gaps to cause spark breakdown of the gaps.

(vi) Voltage Dividers:

Voltage divider of either damped capacitor or resistor type and an oscilloscope with recording arrangement are provided for measurement of the voltage across the test object.

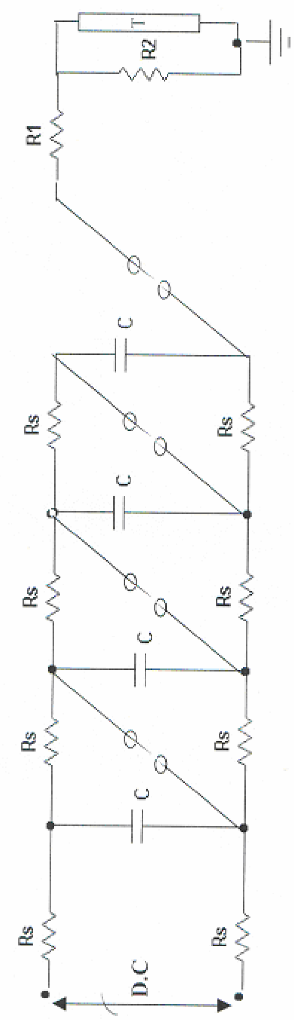


Fig.4.4a Marx circuit (Multistage Impulse Generator)

4.4.2 Operation of Marx Generator: -

The schematic diagram of Marx circuit and its modification are shown in Fig. 4.4 a and 4.4 b, respectively , usually the charging resistors R_s is chosen to limit the charging current to about 50 to 100 mA ,and the generator capacitance C is chosen such that the product CR_s is about 10 s to 1 min .The gap spacing is chosen such that the breakdown voltage of the gap G is greater than the charging voltage V. Thus, all the capacitances are charged to the voltage V in about 1 minute. When the impulse generator is to be discharged, the gaps G are made to spark over simultaneously by some external means .Thus, all the capacitors C get connected in series and discharge into the load capacitance on the test object.

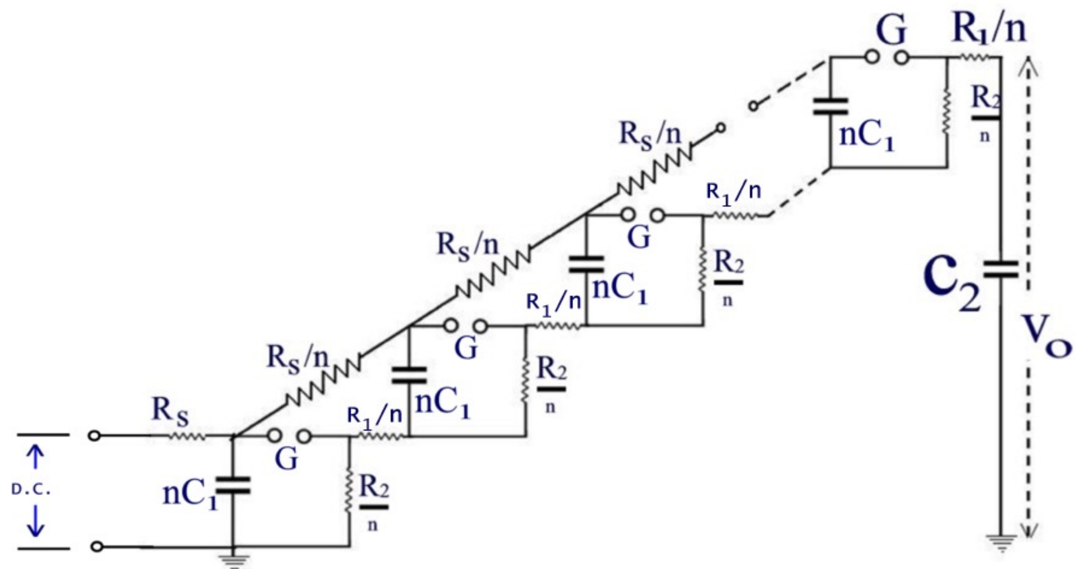


Fig. 4.4.b multistage impulse generator incorporating the series and wave tail resistances within the generator.

In the Marx circuit of Fig. 4.4.a the impulse wave shaping circuit is connected externally to the capacitor unit. In Fig. 4.4 b, the modified Marx circuit is shown, wherein the resistances R_1 and R_2 are incorporated inside the unit. R_1 is divided into n parts equal to R_1/n and put in series with the gap G. R_2 is also divided into n parts and arranged across each capacitor unit after the gap G. This arrangement saves space, and also the cost is reduced .But, in case the wave shape is to be varied widely, the variation becomes difficult. The additional advantages gained by distributing R_1 and R_2 inside the unit are that the control resistors are smaller in size and the efficiency (Vo/nV) is high.

Impulse generators are nominally rated by the total voltage (nominal), the number of stage, and the gross energy stored. The nominal output voltage is the number of stage multiplied by the charging voltage, the nominal energy stared is given by $\frac{1}{2}C_1V^2$ where C_1= c/n (the discharge capacitance) and v is the nominal maximum voltage (n times charging voltage).

Chapter Five

Mathematical analysis of Impulse Generator circuits

5.1 Analysis of Impulse Generator circuit of series R-L-C Type:-

Referring to Fig. 4.3.a the current through the load resistance R is given by:

$$V = \frac{1}{c}\int_0^t idt + Ri + L\frac{di}{dt} \qquad (5.1)$$

With initial condition at t=0 being I (0) =0 and the net charge in the circuit $i = \frac{dq}{dt} = 0$. Using Laplace transform

$$\frac{V}{s} = \left(\frac{1}{\mathrm{cs}} + R + Ls\right)\mathrm{I(s)}$$

Or; $I(s) = \frac{V}{L}\left[\frac{1}{S^2 + \frac{Rs}{L} + \frac{1}{LC}}\right]$

The output voltage V0(s) = I(s) R, hence

$$V_0(s) = \left(\frac{\mathrm{R}}{\mathrm{L}}.V\right)\frac{1}{S^2 + \frac{Rs}{L} + \frac{1}{LC}}$$

For an over damped condition, $\frac{R}{2L} \geq \frac{1}{\sqrt{LC}}$

Hence, the roots of the equation $S^2 + \frac{Rs}{L} + \frac{1}{Lc}$ are

$$\alpha = S_1 = \frac{-R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

$$\beta = S_2 = \frac{-R}{2L} - \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

The solution of the equation for $V_0(t)$ is

$$v_0(t) = \frac{V\left(\frac{R}{2L}\right)}{\left[\frac{R^2}{4L^2} - \frac{1}{LC}\right]^{1/2}}\left[\exp(-\alpha\,\mathrm{t}) - \exp(-\beta\,\mathrm{t})\right] \quad (5.2)$$

$$= \mathrm{V}_0\left[\exp(-\alpha\,\mathrm{t}) - \exp(-\beta\,\mathrm{t})\right] \quad (5.3)$$

$$\therefore V_0 = \frac{V\left(\frac{R}{2L}\right)}{\left[\frac{R^2}{4L^2} - \frac{1}{LC}\right]^{1/2}} = \frac{V}{\left[1 - \frac{4L}{CR^2}\right]^{1/2}} \quad (5.4)$$

The sum of the roots $(\alpha + \beta) = \frac{-R}{2L}$ (5.5)

The product of the roots $\alpha\beta = \frac{1}{LC}$ (5.6)

5.2 Analysis of the other Impulse Generator circuits:-

The most commonly used configuration for impulse generator are the circuits shown in Fig.4.3 b and c.

For the configuration shown in Fig.4.3 b, the output voltage across C_2 is given by, $v_o(t) = \frac{1}{c}\int_1^t i_2 dt.$ (5.7)

Performing Laplace transformation, $\frac{1}{c_2 s} I_2(s) = v_o(s)$

Where i_2 is the current through c_2.

Taking the current through c_1 as i_1 and its transformed value as $I_1(s)$,

$$I_2(s) = \left[\frac{R_2}{R_2 + \frac{1}{c_2 s}}\right] I_1(s)$$

$$I_1(s) = \frac{V}{s}\frac{1}{\frac{1}{c_1 s} + R_1 + \frac{R_2 . \frac{1}{c_2 s}}{R_2 + \frac{1}{c_2 s}}}$$

where, $\dfrac{R_2.\dfrac{1}{c_2 s}}{R_2+\dfrac{1}{c_2 s}}$ represents the impedance of the parallel combination of R_2 and c_2.

Substitution of $I_1(s)$ gives

$$v_o(s)=\frac{1}{c_2 s}\frac{R_2}{R_2+\dfrac{1}{c_2 s}}\frac{V}{s}\frac{1}{\dfrac{1}{c_1 s}+R_1+\dfrac{R_2(1/c_2 s)}{R_2+(1/c_2 s)}}$$

After simplification and rearrangement,

$$v_o(s)=\frac{V}{R_1 c_2}\left[\frac{1}{s^2+\left(\dfrac{1}{c_1 R_1}+\dfrac{1}{c_2 R_2}+\dfrac{1}{c_2 R_1}\right)s+\dfrac{1}{c_1 c_2 R_1 R_2}}\right] \qquad (5.8)$$

Hence, the roots of the equation

$$s^2+\left[\frac{1}{c_1 R_1}+\frac{1}{c_2 R_2}+\frac{1}{c_2 R_1}\right]s+\frac{1}{c_1 c_2 R_1 R_2}$$

Are found from the relations,

$$\alpha+\beta=-\left[\frac{1}{c_1 R_1}+\frac{1}{c_2 R_2}+\frac{1}{c_2 R_1}\right]$$

$$\alpha\beta=\frac{1}{c_1 c_2 R_1 R_2} \qquad (5.9)$$

Taking inverse transform of $v_0(s)$ gives

$$v_o(t)=\frac{V}{R_1 c_2(\alpha-\beta)}\left[\exp(-\alpha t)-\exp(-\beta t)\right] \qquad (5.10)$$

Usually, $\dfrac{1}{c_1 R_1}$ and $\dfrac{1}{c_2 R_2}$ will be much smaller compared to $\dfrac{1}{R_1 c_2}$

Hence, the roots may be approximated as

$$\alpha \approx \frac{1}{R_1 c_2} \text{ and, } \beta \approx \frac{1}{R_2 c_1} \qquad (5.11)$$

Following a similar analysis, it may be shown that the output waveform for the circuit configuration of Fig.4.3 c will be

$$v_o(t) = \frac{VR_2c_1\alpha\beta}{(\beta-\alpha)}\left[\exp(-\alpha t) - \exp(-\beta t)\right] \qquad (5.12)$$

Where α and β are the roots of the Eq. (5.10)

The equivalent circuit given in Fig.4.3 d is a combination of the configuration of Fig.4.3b and Fig .4.3 c. The resistance R_1 is made into two parts and kept on either side of R_2 to give greater flexibility for the circuits.

From the circuit shown in Fig.5.1b the following equation can be written:

$$i_1 = -C_1\frac{dv_1}{dt}$$

$$i_2 = -C_2\frac{dv_2}{dt}$$

$$v_1 - R_1i_1 - R_2(i_1 + i_2) = 0 \qquad (5.13)$$

$$\therefore v_1 + R_1C_1\frac{dv_1}{dt} + R_2C_1\frac{dv_1}{dt} + R_2C_2\frac{dv_2}{dt} = 0$$

$$\therefore v_1 + (R_1C_1 + R_2C_1)\frac{dv_1}{dt} + R_2C_2\frac{dv_2}{dt} = 0 \;\ldots\ldots\; (5.14)$$

$$v_2 - R_2(i_1 + i_2) = 0 \qquad (5.15)$$

$$\therefore v_2 + R_2C_2\frac{dv_2}{dt} + C_1R_2\frac{dv_1}{dt} = 0 \quad \ldots\ldots\ldots\ldots \; (5.16)$$

Equations (5.14) and (5.16) can be represented by the block diagram shown in Fig.5.2.

The performance of the circuit shown in Fig.5.1c is described mathematically, by the equations

$$i_1 = -C_1\frac{dv_1}{dt}$$

$$i_2 = C_2\frac{dv_2}{dt}$$

$$v_1 - R_2(i_1 - i_2) = 0 \qquad (5.17)$$

$$\therefore v_1 + R_2 C_1 \frac{dv_1}{dt} + R_2 C_2 \frac{dv_2}{dt} = 0 \;\; \ldots\ldots\ldots\ldots \qquad (5.18)$$

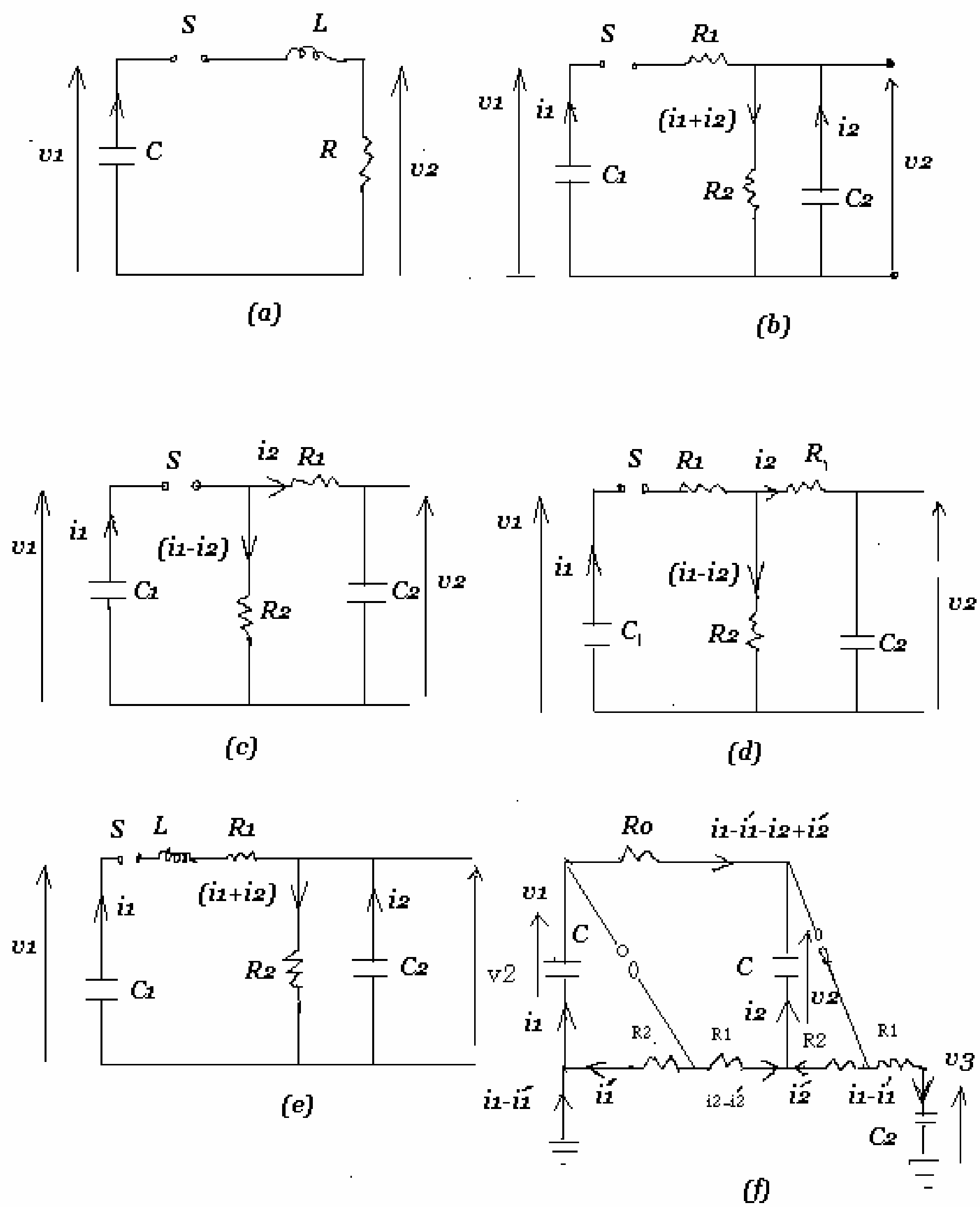


Fig.5.1

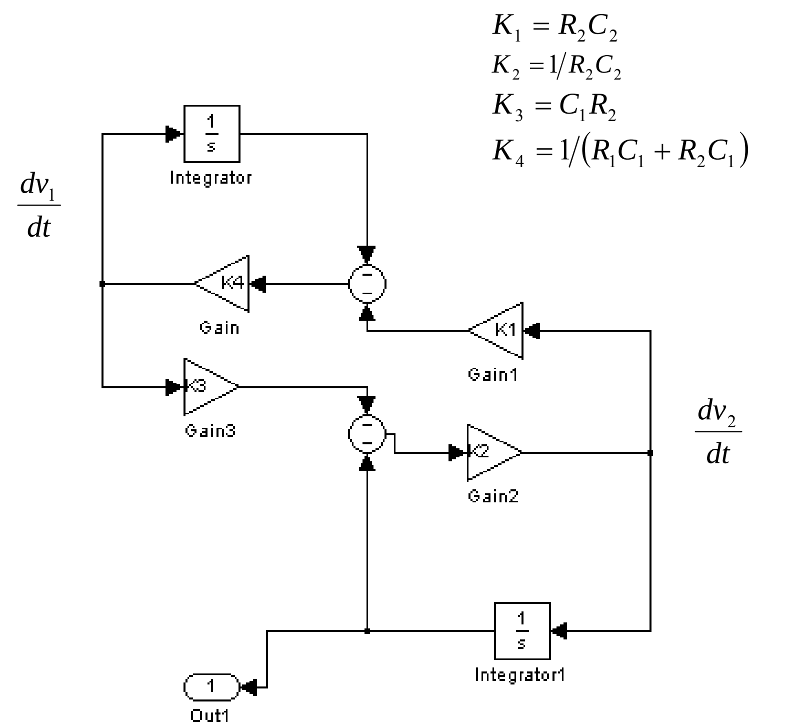


Fig. 5.2 Block diagram of the circuit shown in Fig. 5.1b

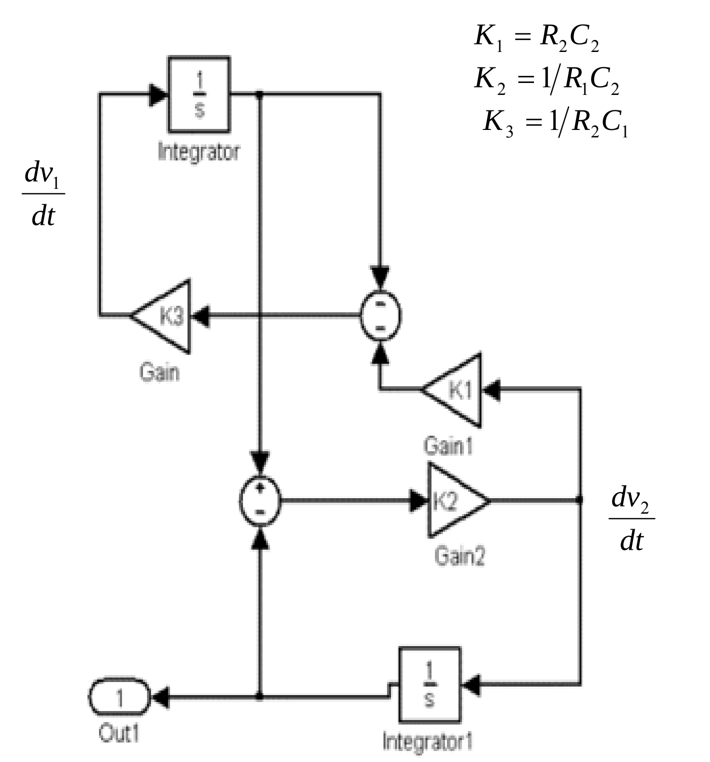


Fig. 5.3 Block diagram of the circuit shown in Fig. 5.1c

$$v_1 - i_2 R_1 - v_2 = 0 \qquad (5.19)$$

$$\therefore v_1 - v_2 - R_1 C_2 \frac{dv_2}{dt} = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ .\ (5.20)$$

Equations (5.18) & (5.20) can be represented by the block diagram shown in Fig.5.3.

The performance of the circuit shown in Fig.5.1d is described mathematically, by the equations

$$i_1 = -C_1 \frac{dv_1}{dt} \quad \text{and} \quad i_2 = C_2 \frac{dv_2}{dt}$$

$$v_1 - R_1 i_1 - R_2 (i_1 - i_2) = 0 \qquad (5.21)$$

$$\therefore v_1 + R_1 C_1 \frac{dv_1}{dt} + R_2 C_1 \frac{dv_1}{dt} + R_2 C_2 \frac{dv_2}{dt} = 0$$

$$\therefore v_1 + (R_1 C_1 + R_2 C_1) \frac{dv_1}{dt} + R_2 C_2 \frac{dv_2}{dt} = 0 \ \ldots\ldots\ . \qquad (5.22)$$

$$v_2 + R_1 i_2 - R_2 (i_1 - i_2) = 0 \qquad (5.23)$$

$$\therefore v_2 + (R_2 C_2 + R_1 C_2) \frac{dv_2}{dt} + R_2 C_1 \frac{dv_1}{dt} \qquad \ldots\ldots\ldots\ (5.24)$$

Equations (5.22) and (5.24) can be represented by the block diagram shown in Fig.5.4.

The performance of the circuit shown in Fig.5.1e is described mathematically, by the equations

$$i_1 = -C_1 \frac{dv_1}{dt}$$

$$i_2 = -C_2 \frac{dv_2}{dt}$$

$$v_1 - R_1 i_1 - L \frac{di_1}{dt} - R_2 (i_1 + i_2) = 0 \qquad (5.25)$$

$$\therefore v_1 + R_1 C_1 \frac{dv_1}{dt} + L C_1 \frac{d^2 v_1}{dt^2} + R_2 C_1 \frac{dv_1}{dt} + R_2 C_2 \frac{dv_2}{dt} = 0 \qquad (5.26)$$

$$\therefore v_1 + (R_1 C_1 + R_2 C_1) \frac{dv_1}{dt} + L C_1 \frac{d^2 v_1}{dt^2} + R_2 C_2 \frac{dv_2}{dt} = 0 \ \ldots\ldots\ldots\ldots \qquad (5.27)$$

$$v_2 - R_2 (i_1 + i_2) = 0 \qquad (5.28)$$

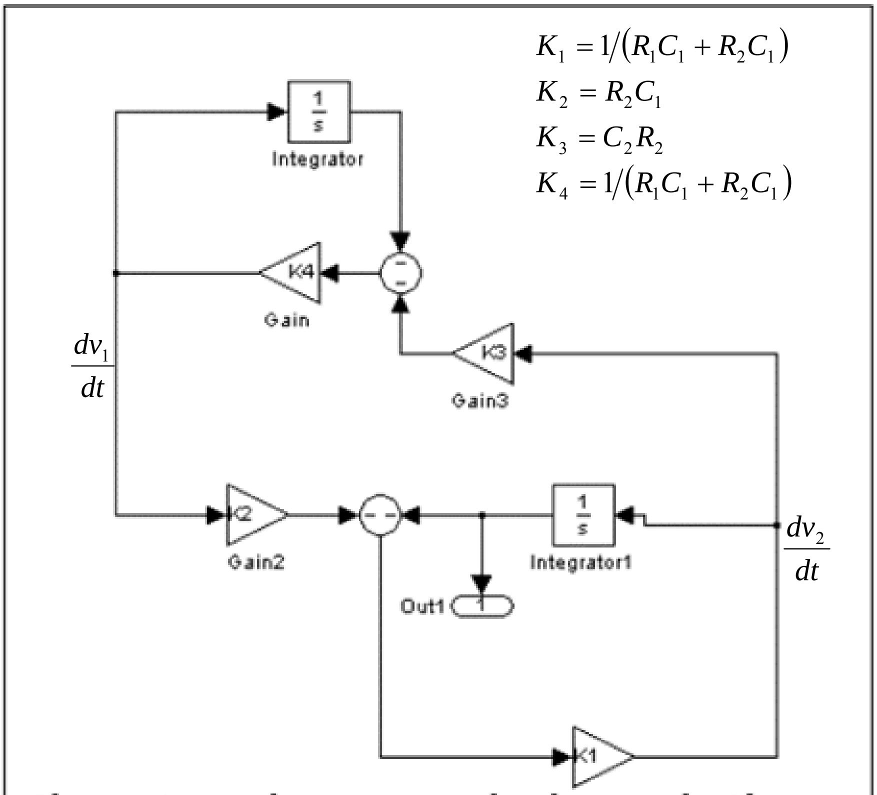


Fig. 5.4 Block diagram of the circuit shown in Fig. 5.1d

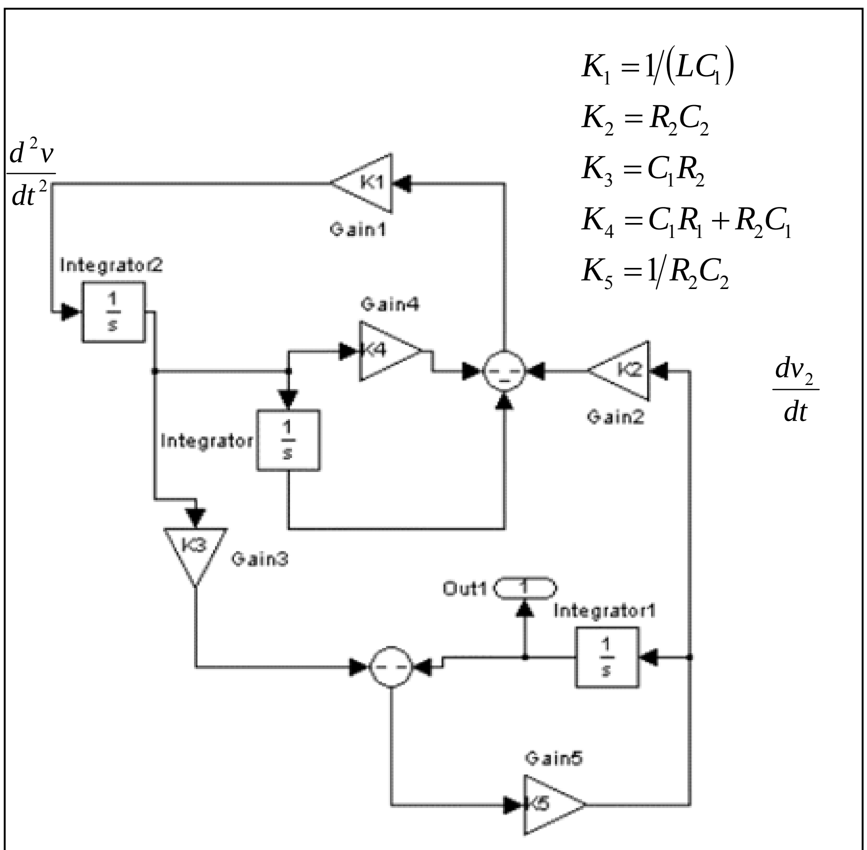


Fig. 5.5 Block diagram o f the circuit shown inFig.5.1e

$$\therefore v_2 + R_2C_2\frac{dv_2}{dt} + R_2C_1\frac{dv_1}{dt} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5.29)$$

Equations (5.27) and (5.29) can be represented by the block diagram shown in Fig.5.5

The performance of the circuit shown in Fig.5.1f, which represent a two – stage Marx generator is described mathematically, by the equations:

$$i_1 = -C\frac{dv_1}{dt} \qquad (5.30)$$

$$i_2 = -C\frac{dv_2}{dt} \qquad (5.31)$$

$$v_1 = i_1^{/}R_2 \Rightarrow i_1^{/} = \frac{v_1}{R_2} \qquad (5.32)$$

$$v_2 = i_2^{/}R_2 \Rightarrow i_2^{/} = \frac{v_2}{R_2} \qquad (5.33)$$

$$v_2 + (i_1 - i_1^{/} - i_2 + i_2^{/})R_O - (i_2 - i_2^{/})R_1 = 0 \qquad (5.34)$$

From (5.30),(5.31),(5.32) , (5.33) and (5.35) the following equation can be obtained

$$\therefore v_2 + i_1R_O - i_1^{/}R_O - (R_O + R_1)i_2 + (R_O + R_1)i_2^{/} = 0 \qquad (5.35)$$

$$\therefore v_2 - CR_O\frac{dv_1}{dt} - \frac{R_O}{R_2}v_1 + (R_O + R_1).C\frac{dv_2}{dt} + \frac{(R_O + R_1)}{R_2}v_2 = 0 \qquad (5.36)$$

$$\therefore (1 + \frac{R_O + R_1}{R_2})v_2 - \frac{R_O}{R_2}v_1 - R_OC\frac{dv_1}{dt} + (R_O + R_1)C\frac{dv_2}{dt} = 0 \qquad (5.37)$$

$$(i_1 - i_1^{/}) = C_2\frac{dv_3}{dt} \qquad (5.38)$$

$$\therefore C\frac{dv_1}{dt} + \frac{v_1}{R_2} = -C_2\frac{dv_3}{dt} \qquad (5.39)$$

$$v_1 - (i_2 - i_2^{/})R_1 + v_2 - (i_1 - i_1^{/})R_1 - v_3 = 0 \qquad (5.40)$$

$$\therefore v_1 + R_1 C\frac{dv_2}{dt} + \frac{R_1}{R_2}v_2 + v_2 + R_1 C\frac{dv_1}{dt} + \frac{R_1}{R_2}v_1 - v_3 = 0 \quad (5.41)$$

$$\therefore (1+\frac{R_1}{R_2})v_1 + (1+\frac{R_1}{R_2})v_2 + R_1 C\frac{dv_2}{dt} + R_1 C\frac{dv_1}{dt} - v_3 = 0 \quad (5.42)$$

From equations (5.37), (5.39) and (5.42) the block diagram shown in Fig.5.6 can be represented, where $K_1 = R_O C$, $K_2 = \frac{R_O}{R_2}$,

$K_3 = (1 + R_O/R_2 + R_1/R_2)$, $K_4 = 1/(R_O C + R_1 C)$, $K_5 = R_1 C$, $K_6 = 1 + R_1/R_2$

$K_7 = 1 + R_1/R_2$ $K_8 = 1/(R_1 C)$, $K_9 = \frac{1}{R_2}$ and $K = \frac{1}{C_2}$

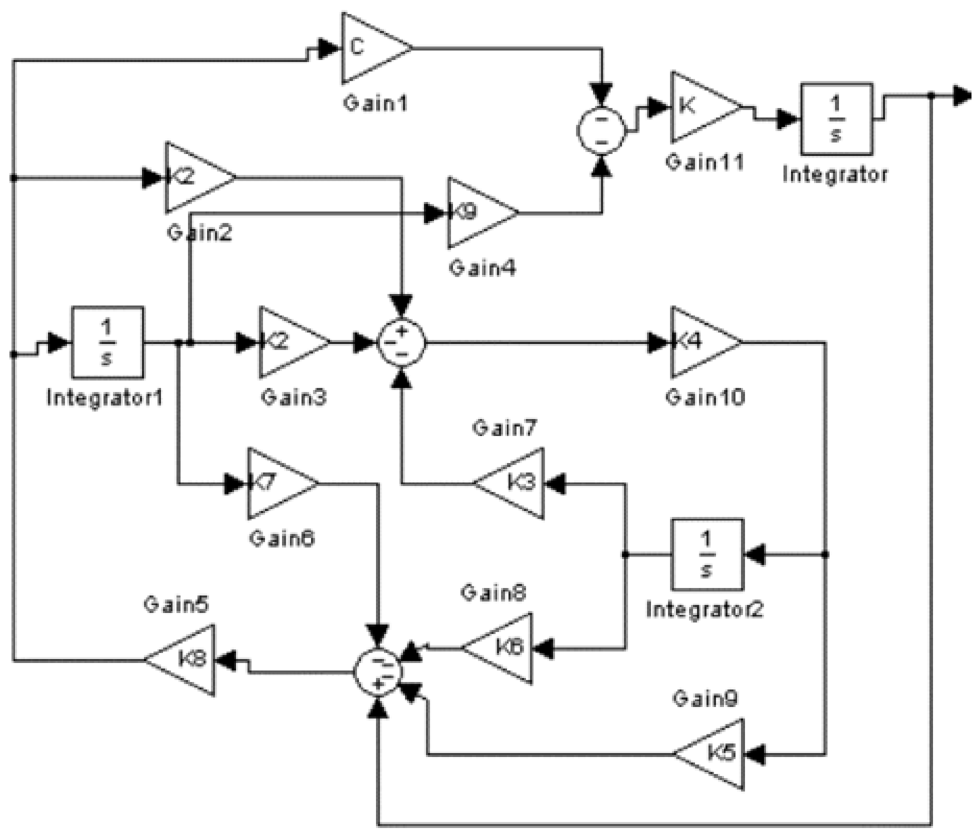


Fig. 5.6 Block diagram of the circuit shown in Fig. 5.1

Chapter Six

Computer Results

The wave shape for the form of impulse generator circuits shown in Figures 5.1b, 5.1c and 5.1d has been analysed and is shown in figures 6.1, 6.2, 6.3, 6.4, 6.5 and 6.6. As the wave front resistance is increased the magnitude of the peak value of the wave is decreased. On the other hand as the wave tail resistance is increased the magnitude of the peak value of the wave is increased also. From the general features R_1 will primarily damp the circuit and control the front time while R_2 will discharge the capacitors and therefore essentially control the wave tail.

The influence of the wave front resistance, the series inductance, and the load capacitance on the wave shape for the form of impulse generator circuit of Fig.5.1e has been analysed by Matlap program and is shown in Figures 6.7, 6.8 and 6.9. In Fig.6.7, as the series resistance is increased the oscillation are damped out and the magnitude of the peak value of the waves is decreased; the wave front first decreases until a critical value of series resistance is reached after which it increases . With varying series inductance, as in Fig.6.8, both the wave front and the duration(time to half value) of the wave have minimal values for slightly different values of inductance, but the magnitude of the peak value varies little for the chosen range of inductance. With varying load capacitance, both the wave front and the duration of the wave have minimal values at about the same value of load capacitance, as shown in Fig.6.9.

Fig.5.1f shows a two-stage Marx circuit, from the results shown in figures 6.10 and 6.11 the magnitude of the peak value is approximately doubled comparing to the single –stage ones.

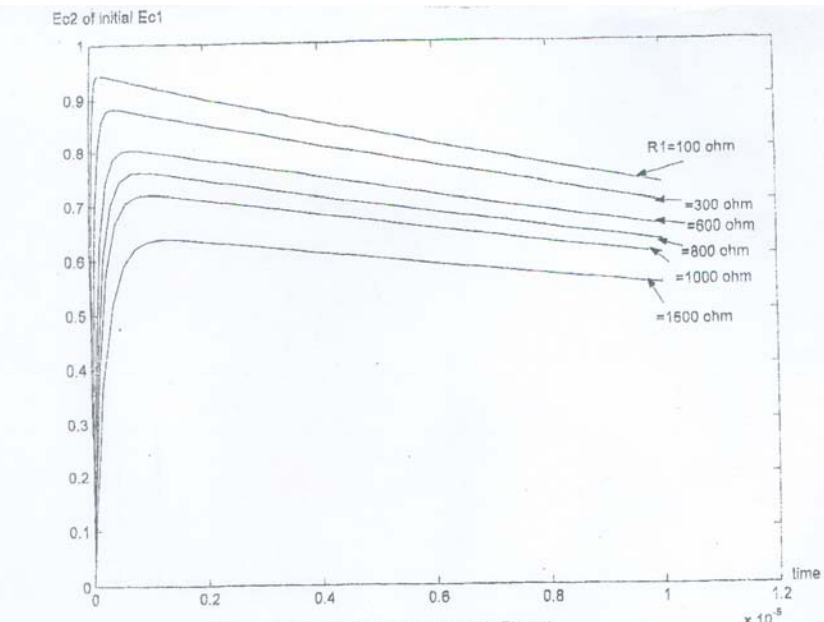


Fig.6.1 Varying R1of the circuit shown in Fig.5.1b

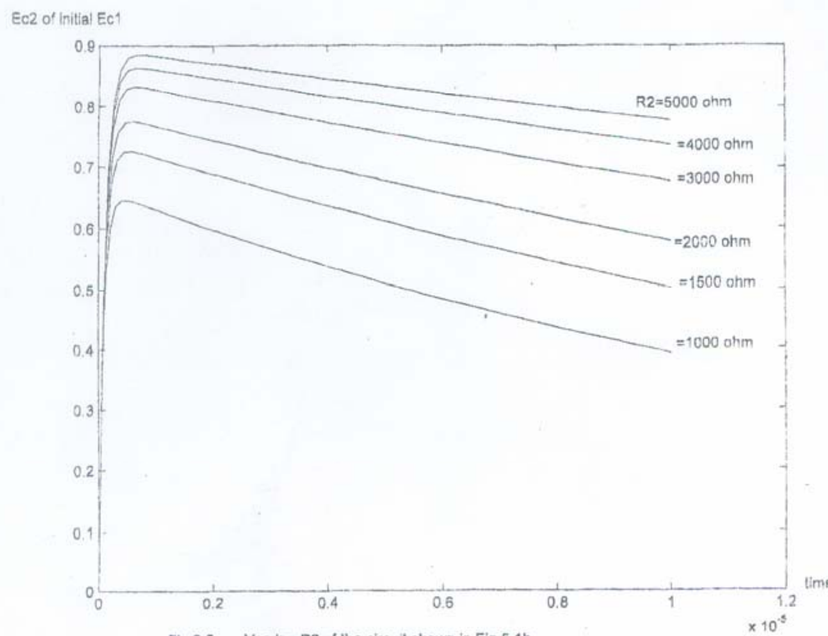


Fig.6.2 Varying R2 of the circuit shown in Fig.5.1b

45

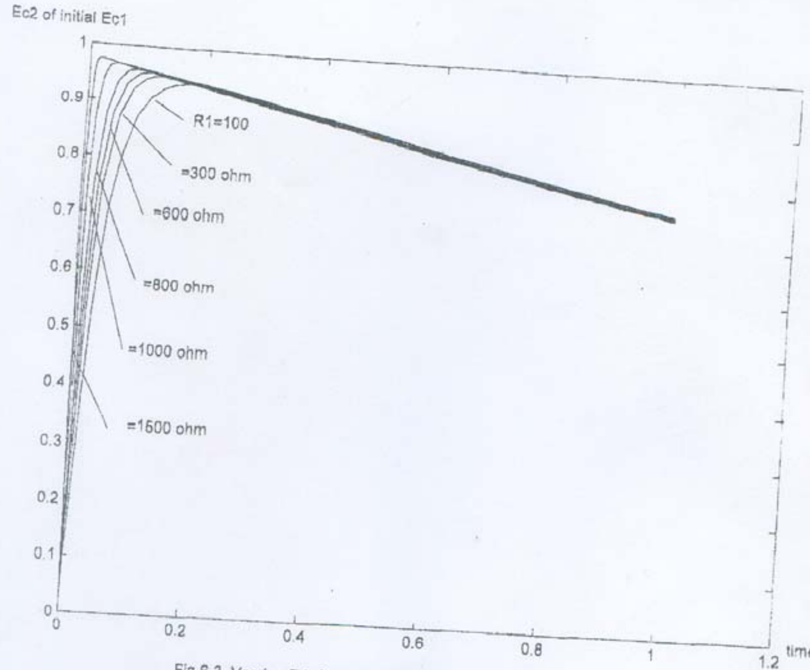


Fig 6.3 Varying R1of the circuit shown in Fig.5.1c

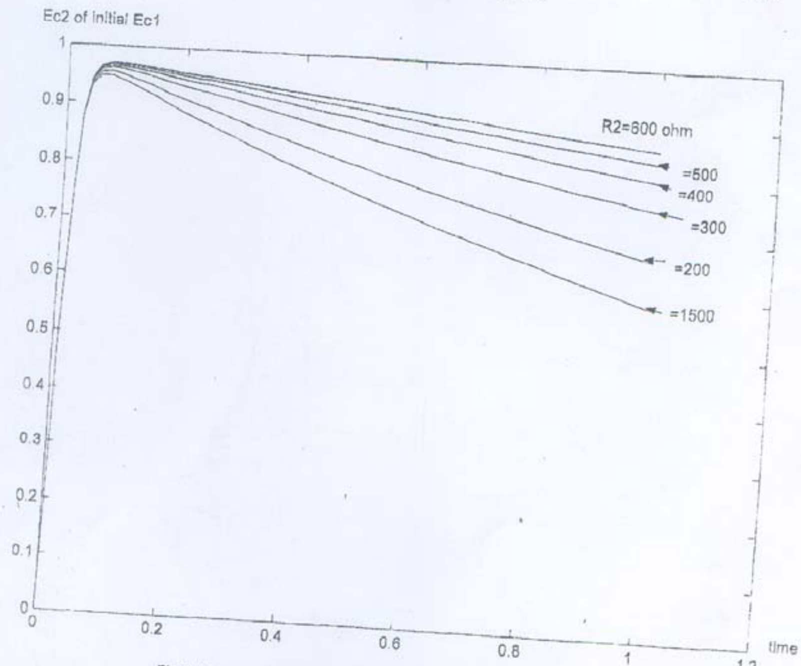


Fig.6.4 Varying R2 of the circuit shown in Fig.5.1c

46

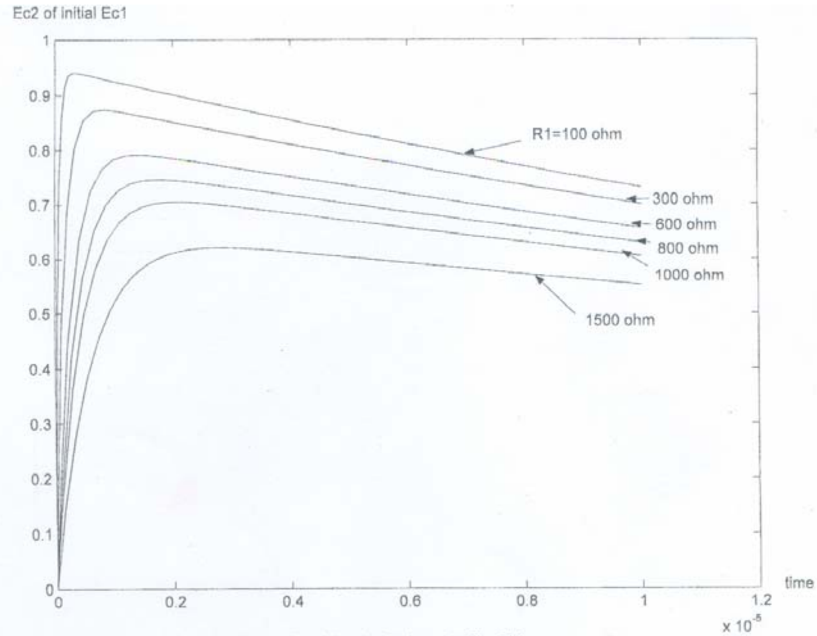


Fig.6.5 Varying R1 of the circuit shown in Fig.5.1d

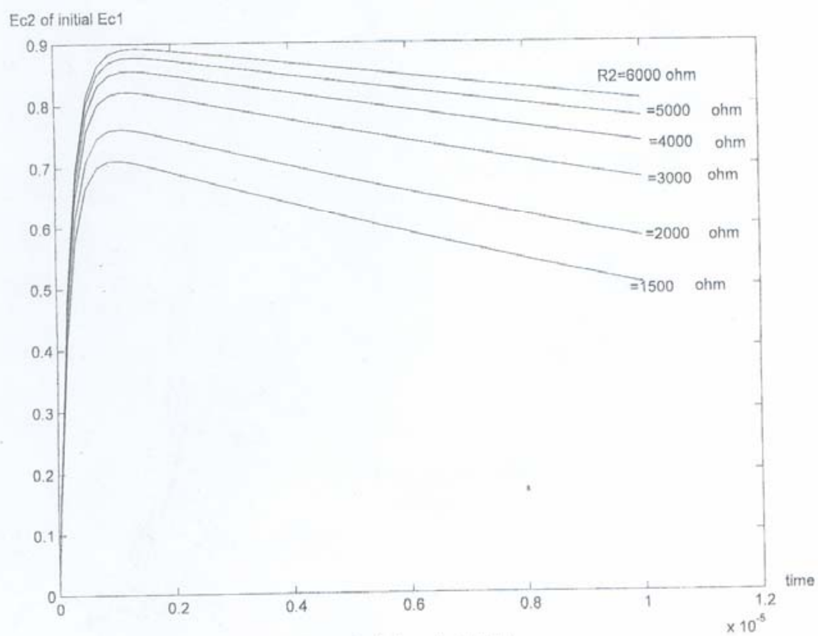


Fig.6.6 Varying R2 of the circuit shown in Fig.5.1d

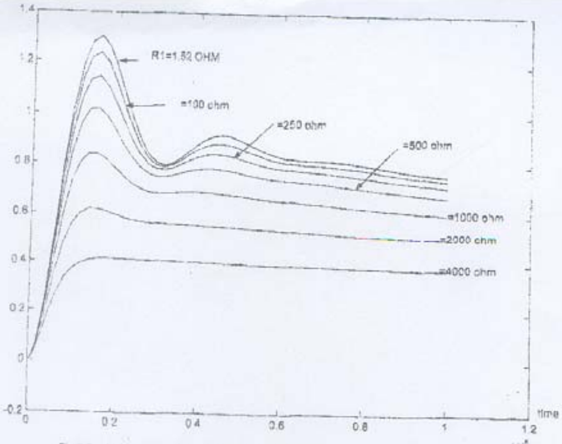


Fig 6.7 Varying R1 of the circuit shown in Fig.5.1e

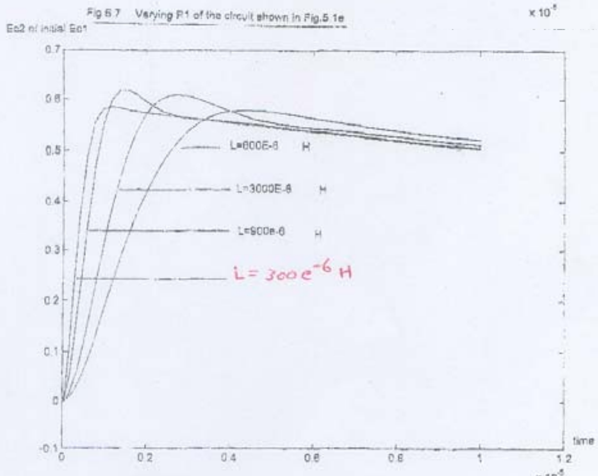


Fig.6.8 Varying L of the circuit shown in Fig.5.1e

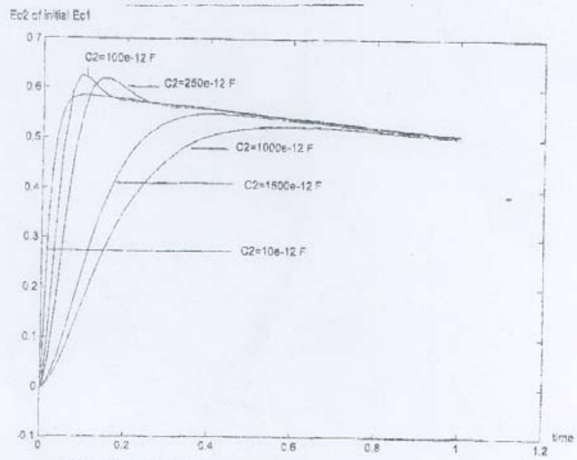


Fig.6.9 Varying C2 of the circuit shown in Fig.5.1e

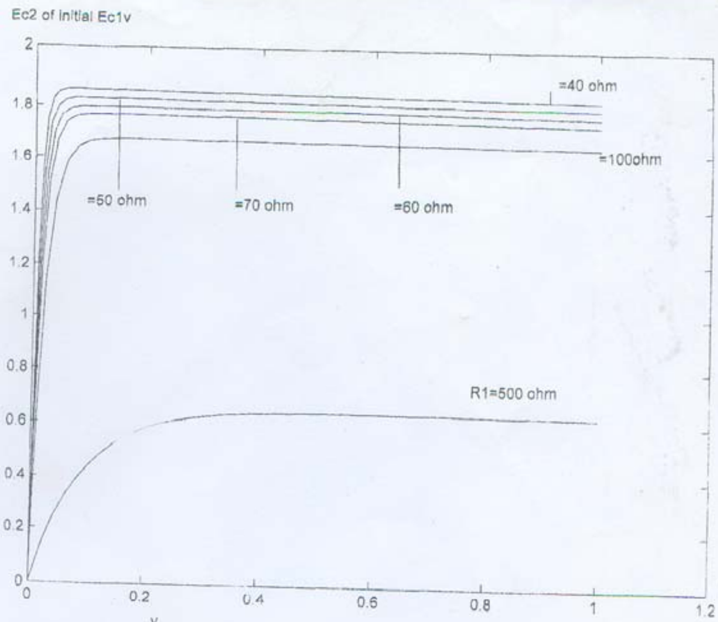


Fig.6.10 Varying R1 of the circuit shown in Fig.5.1f

chapter Seven

Conclusion

● It is essential to ensure that the electrical equipment is capable of withstand the lightning over voltages and switching over voltages. Hence, the impulse testing is necessary.

● The impulse wave are generally represented by the Eq. (4.1) given earlier. V_O in the equation represents a factor that depends on the peak value. α and β control the front and tail time of the wave respectively.

● The advantage of the circuits shown in Fig.4.3.b and c are that the wave front and wave tail times are independently controlled by changing either R_1 or R_2 separately. Secondly, the test object which are mainly capacitive in nature form apart of C_2. Generally, for Impulse generator of Fig.4.3 b or c the generator capacitance C_1 and load capacitance C_2 will be fixed depending on the design of the generator and the test object. Hence, the desired wave shapes is obtained by controlling R_1 and R_2 . R_2 will be large. Taking the circuit inductance to be negligible during charging, C_1 charges the load capacitance c_2 through R_1.Then the time taken for charging is approximately three times the time constant of the circuit and is gives by

$$t_1 = 3.0\, R_1 \frac{C_1 C_2}{C_1 + C_2} = 3R_1\, C_e$$

$$where \;\; c_e = \frac{C_1 C_2}{C_1 + C_2}$$

If R_1 is given in ohms and C_e in micro farads, t_1 is obtained in microsecond .For discharging or tail time, the capacitance c_1 and c_2 may be considered to be in parallel and .discharging occurs through R_1 and R_2 hence, the time for 50% discharge is approximately given by

$t_2 = 0.7(R_1 + R_2)(C_1 + C_2)$

These formulas for t_1 and t_2 hold good for the equivalent circuits shown in Fig. 4.3 b and c. For the circuit given in Fig. 4.3d, R is to be taken as $2R_1$.

● For a given output voltage on multistage generator the lower the d.c. charging voltage the greater must be the number of stages in the generator.

References:

1. High Voltage Engineering
   Kuffel, E.and Abdulla ,Pergaman Press, Oxford (1970)
2. High Voltage Engineering
   E.Kuffel and W.S.Zaengl
3. High Voltage Laboratory Tequniques
   J.D.Craggs and J.M.Meek
4. Thomason, J.L.Trans.Amer. Inst.Engrs. 43, (1934) 322
5. Thomason, J.L.Trans.Amer. Inst.Engrs.,56,(1937) 183

Appendix 1

```
R=[100 300 600 800 1000 1500];
for i=1:6;
R1=R(i)
C1=0.0125E-6
C2=0.00025E-6;
R2=2900;
K1=R2*C2;
K2=1/(R2*C2);
K3=C1*R2;
K4=1/(R1*C1+R2*C1);
sim('HAMODA2',10E-6);
plot(tout,yout);
hold on
end
```

Appendix 2

```
R=[1000 1500 2000 3000 4000 5000];
for i=1:6;
 R2=R(i)
C1=0.0125E-6
C2=0.00025E-6;
R1=500;
K1=R2*C2;
K2=1/(R2*C2);
K3=C1*R2;
K4=1/(R1*C1+R2*C1);
sim('HAMODA2',10E-6);
plot(tout,yout);
hold on
end
```

Appendix 3

```
R=[100 300 600 800 1000 1500];
for i=1:6
R1=R(i);
C1=0.0125E-6;
C2=0.00025E-6
R2=2900
K1=R2*C2;
K2=1/(R1*C2);
K3=1/(C1*R2);
sim('HAMODA3',10E-6);
plot(tout,yout);
hold on
end
```

Appendix 4

```
R=[1500 2000 3000 4000 5000 6000 ];
for i=1:6
R1=R(i);
  C1=0.0125E-6;
C2=0.00025E-6;
R2=2900
K1=R2*C2;
K2=1/(R1*C2);
K3=1/(C1*R2);
sim('HAMODA3',10E-6);
plot(tout,yout);
hold on
end
```

Appendix 5

```
R=[10 30 600 800 1000 1500];
for i=1:6;
   R1=R(i);
C1=0.0125E-6;
C2=0.00025E-6;
R2=2900;
K1=1/(R1*C1+R2*C1);
K2=(R2*C1);
K3=(C2*R2);
K4=1/(R2*C2+R1*C2);
sim('HAMODA4',10E-6);
plot(tout,yout);
hold on
end
```

Appendix 6

```
R=[1500 2000 3000 4000 5000 6000];
for i=1:6;
   R2=R(i);
C1=0.0125E-6;
C2=0.00025E-6;
R1=500;
K1=1/(R1*C1+R2*C1);
K2=(R2*C1);
K3=(C2*R2);
K4=1/(R2*C2+R1*C2);
sim('HAMODA4',10E-6);
plot(tout,yout);
hold on
end
```

Appendix 7

```
H=[1.52 100 250 500 1000 2000 4000];
for i=1:7
   R1=H(i);
C1=0.0125E-6;
C2=0.00025E-6
R2=2900;
L=900E-6
K1=1/(L*C1);
K2=(R2*C2);
K3=C1*R2;
K4=C1*R1+R2*C1;
K5=1/(R2*C2);
sim('HAMODA5',10E-6);
plot(tout,yout);
hold on
end
```

Appendix 8

```
H=[300E-6 600E-6 900E-6 3000E-6];
for i=1:5
L=H(i);
C1=0.0125E-6;
C2=0.00025E-6
R1=2000;
R2=2900;
K1=1/(L*C1);
K2=(R2*C2);
K3=C1*R2;
K4=C1*R1+R2*C1;
K5=1/(R2*C2);
sim('HAMODA5',10E-6);
plot(tout,yout);
hold on
end
```

Appendix 9

```
H=[10E-12 100E-12 250E-12 1000E-12 1500E-12];
for i=1:5
C2=H(i);
C1=0.0125E-6;
R1=2000;
R2=2900;
L=900E-6;
K1=1/(L*C1);
K2=(R2*C2);
K3=C1*R2;
K4=C1*R1+R2*C1;
K5=1/(R2*C2);
sim('HAMODA5',10E-6);
plot(tout,yout);
hold on
end
```

Appendix 10

```
R=[40 50 60 70 100 500 ];
for i=1:6;
R1=R(i);
Ro=2000;
C=10e-6;
C2=10e-9;
K1=Ro*C;
K2=Ro/R2;
K3=(1+Ro/R2+R1/R2);
K4=1/(Ro*C+R1*C);
K5=R1*C;
K6=(1+R1/R2);
K7=(1+R1/R2);
K8=1/(R1*C);
K9=1/Rt
k=1/C2
E=1;
sim('HAMODA',0.0001);
plot(tout,yout);
hold on
end
```

Appendix11

```
R=[100 200 300 400 500 6000 ];
for i=1:6;
R2=R(i);
Ro=2000;
R1=50;
C=10e-6;
C2=10e-9;
K1=Ro*C;
K2=Ro/R2;
K3=(1+Ro/R2+R1/R2);
K4=1/(Ro*C+R1*C);
K5=R1*C;
K6=(1+R1/R2);
K7=(1+R1/R2);
K8=1/(R1*C);
K9=1/R2
k=1/C2
sim('HAMODA',0.0001);
plot(tout,yout);
hold on
end
```