Chapter 1

Using the Impedance Diagram

- Using impedance diagrams for load flows
- Using impedance diagrams for fault calculations

By the end of this synchronous session you should be comfortable with how impedance diagrams can be used to calculate load flows and perform fault calculations in an electrical power system

1.1 Load Flow Calculation

1.1.1 Load flow

- In an electrical power system currents flow from generators to loads via a transmission/distribution system therby permitting 'load (power) flows'
- If a system is at steady-state then currents and power flows would be stable
- If there is a change in the system e.g. suddenly and additional load is connected, then there will be a change to currents and load flow
- An electrical system cannot change instantaneously from one state to another. The generators for example cannot instantaneously change the supply of power at the point load changes. There will be a transient period

1.1.2 Load flow analysis example

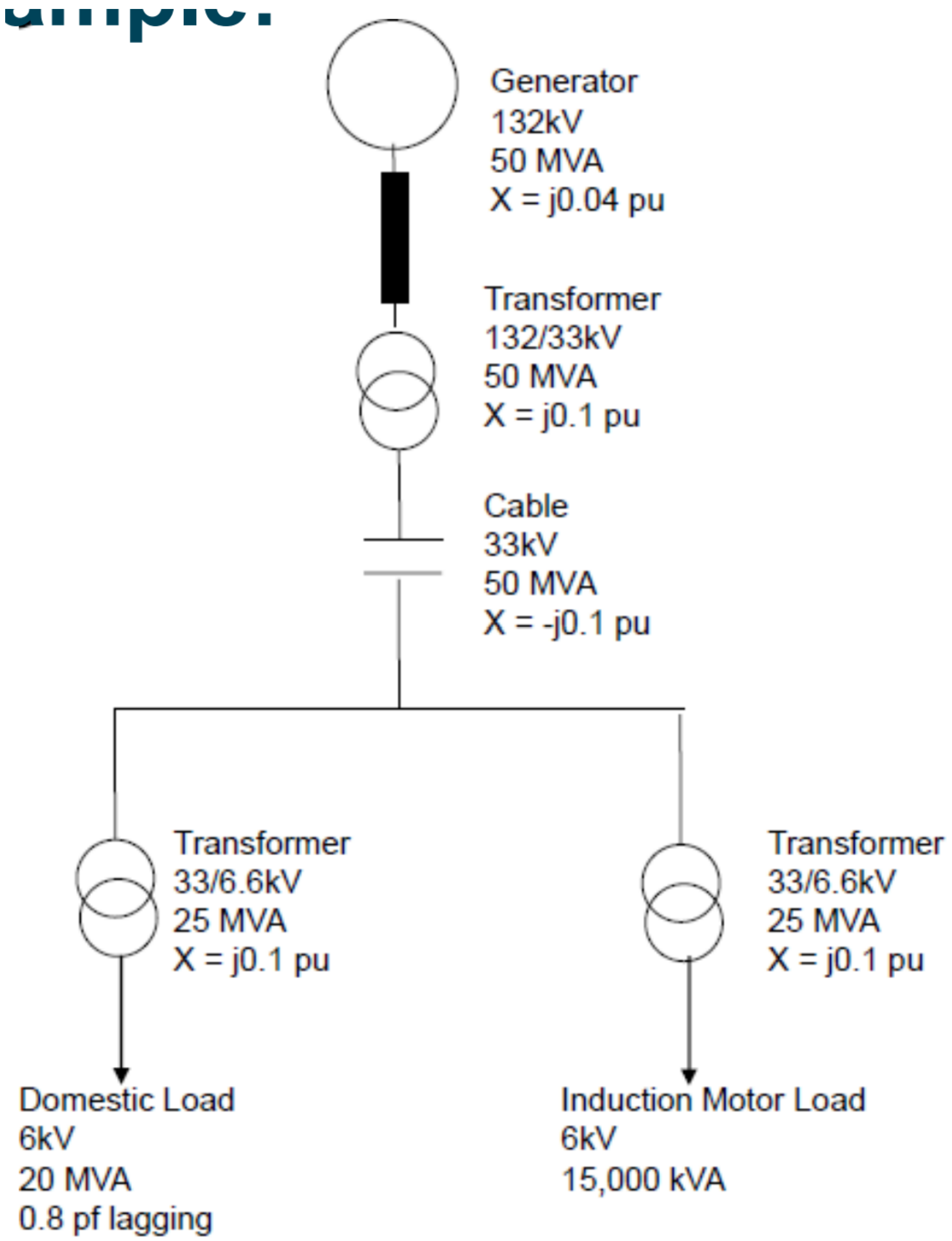

Figure 1.1: Single Line Diagram.

A 132 kV supply feeds two loads; a group of domestic consumers and a group of induction motors which on starting consume five times rated (or design) full load current at zero power factor lagging.

Part a

Convert the single line diagram into an impedance diagram. We will select a base S of 50 MVA and 33 kV as the base V. The values selected can be different but must be stated by the designer.

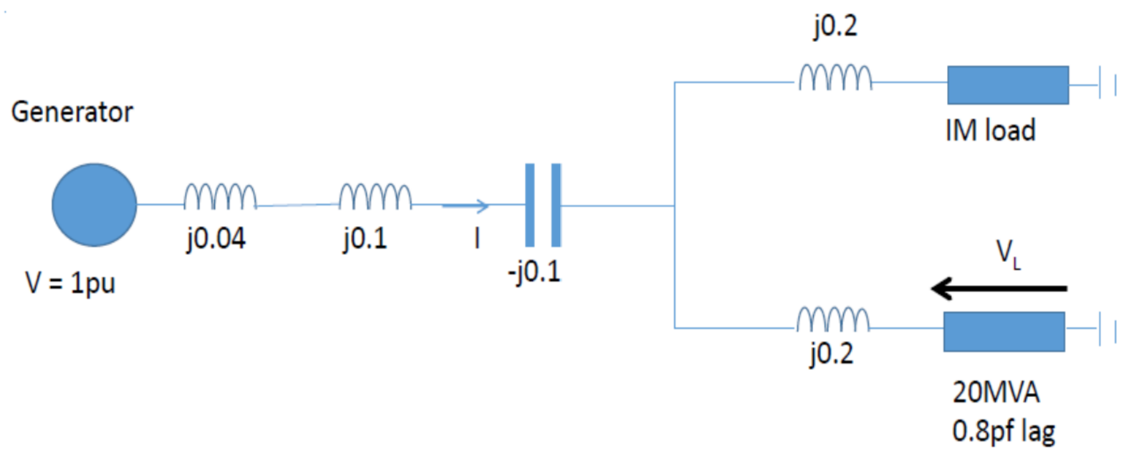

Figure 1.2: Single Line Diagram.

Here is the Impedance Diagram of the Single Line Diagram where all the impedances have been changed into per unit values on a 50 MVA base.

Part b

Calculate the voltage at the domestic busbars prior to induction motor start.

- The induction motor load is open circuit so all current flowing from the generator will flow to the domestic load i.e. steady state
- To determine the voltage at the domestic busbar prior to the induction motor start then the equation for $V_L = 1 - IZ$ can be used, where:
  - V_L is the domestic voltage
  - 1 is the pu voltage at the generator
  - I is the generator current
  - Z is the system impedance between source and load

Calculating the impedance of the circuit then:

$$Z = j\,(0.04 + 0.1 - 0.1 + 0.2) = j0.24 \tag{1.1}$$

Calculating the current in the circuit then:

$$I = \frac{20 \times 10^6}{\sqrt{3} \times 6000} = 1925\,\text{A at 0.8 pf lag} \tag{1.2}$$

Now defining base current related to domestic side (although the domestic side is rated at 6 kV, the transformer is rated at 6.6 kV and it is permissible to use this values as it is correct in the SLD and ID), we can say:

$$\text{Base current at } 6.6\,\text{kV} = \frac{50 \times 10^6}{\sqrt{3} \times 6.6 \times 10^3} = 4374\,\text{A} \tag{1.3}$$

$$\text{Domestic current pu } = \frac{1925}{4374} = 0.44 \text{ at } 0.8 \text{ pf lag} \tag{1.4}$$

$$V_L' = 1 - j0.04\left[0.44\,(0.8 - j0.6)\right] - j0.2\left[0.44\,(0.8 - j0.6)\right] = 0.94\,\text{pu} \tag{1.5}$$

Part c

Calculate the maximum voltage dip that will occur when all the induction motors are started together at the same moment in time. The induction motor switch is now closed. The demand at this moment is five times normal full-load current. The induction motor load demands a substantial current:

$$\text{Starting current IM} = -j\frac{15000 \times 10^3}{\sqrt{3} \times 6000} \times 5 = -j7217\,\text{A} \tag{1.6}$$

$$\text{Starting current IM} = -j\frac{7217}{4374} = -j1.64\,\text{pu} \tag{1.7}$$

The induction motor load demands a substantial current which flows from the generator. Remember at IM start there is no real power so all power is reactive hence zero power factor. The voltage at the terminals will drop across the series connected devices:

$$V_L' = 1 - j0.04\left[0.44\,(0.8 - j0.6) - j1.64\right] - j0.2\left[0.44\,(0.8 - j0.6)\right] \tag{1.8}$$

$$= 0.871 - j0.084 = 0.875\,\text{pu} \tag{1.9}$$

Hence the voltage dips from 0.94 pu to 0.87 pu or alternatively from 6.204 kV to 5.78 pu. The voltage dip would be noticed temporarily as a light flicker or dimming. In practice, the generator would recover after a few seconds - transient response of the generator.

1.1.3 Some thoughts

- Understand the initial conditions first and then calculate the impact of load changes
- The line series capacitor installed has partially neutralised the network inductance. Without this capacitance the dip would be much more severe
- Voltage flicker often occurs when there is a sudden demand for large power is demanded e.g. starting of large induction motors on ships or in grids e.g. near steel rolling mills or factories

1.2 Using impedance diagrams in short-circuit balanced faults

1.2.1 Fault classification

Faults may be classified as being:

- Open circuit faults
- Short circuit faults

Faults may occur in high voltage and low voltage systems meaning:

- Three-ohase system faults
- Single-phase system faults
- DC system faults

For short circuit fault types then the engineer needs to appreciate its significance and protect against such events. Faults have two main characteristics: MVA fault level (MVA) and fault current (I_{fault}).

1.2.2 Types of faults

Symmetrical fault (Fault currents are balanced in each phase)

- Three-phase short circuit
- Three-phase to ground fault
- (Three-phase open circuit)

Unsymmetrical fault (fault currents are **not** balanced in each phase)

- Single-phase to earth
- Double-phase to earth
- Two-phases short together
- Single-phase open circuit
- Double-phase open circuit

1.2.3 Faults normally are due to:

- Wearing of insulation
- Aging
- Poor connections
- Fault due to lightning
- Tree limbs falling on the line
- Wind, weather impacts
- Impact/shock damage
- Vandalism
- Poor safety protocols or work on live equipment

1.2.4 MVA method

- The MVA method is used to define the power at the point of a fault
- The accepted method is to calculate the Fault MVA as follows:

$$MVA_{fault} = \frac{\text{Base S (MVA)}}{\text{Impedance to fault (pu)}} \tag{1.10}$$

- Having calculated the MVA_{fault} the fault current can be calculated using the nominal voltage at the fault

$$I_{fault} = \frac{\text{MVA}_{fault}}{\sqrt{3} times V_{base}} \tag{1.11}$$

1.2.5 Balanced three-phase fault

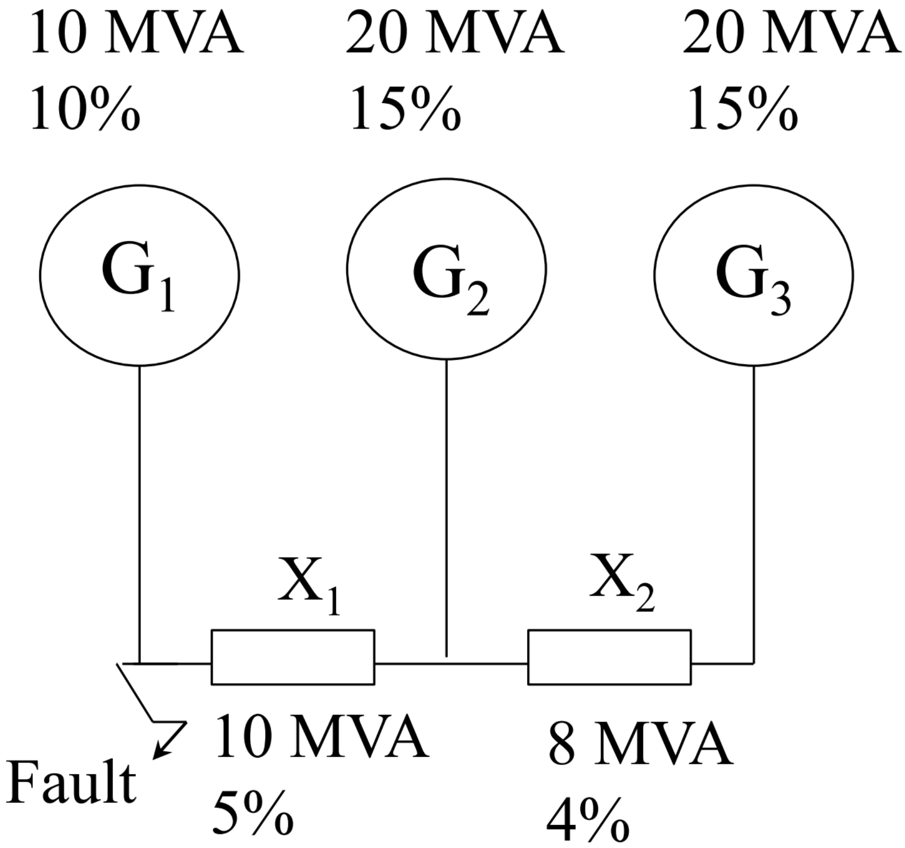

Figure 1.3: Balanced three-phase fault.

An interconnected generator-reactor system is active and suddenly incurs a balanced three-phase short circuit at the Fault indicated. Using a 50 MVA base then draw an impedance diagram and hence determine the Fault Level and Fault Current. It is an 11 kV three phase system.

1.2.6 Solution

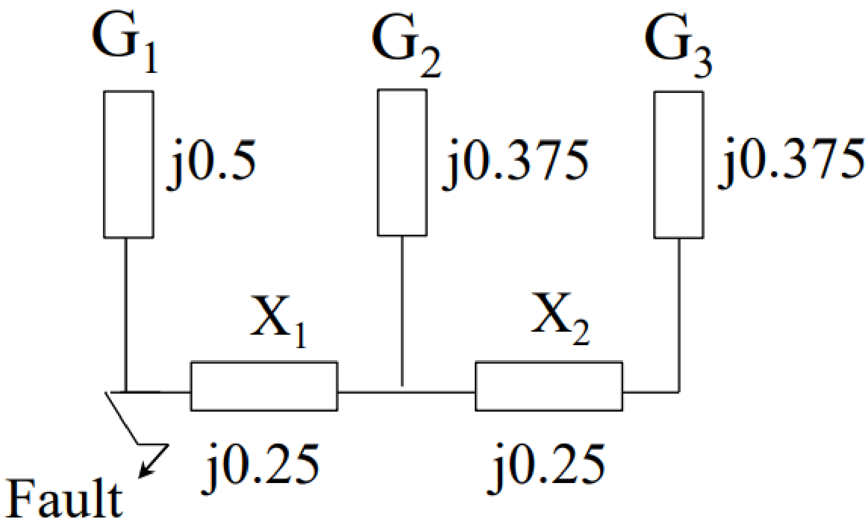

Figure 1.4: Impedance diagram.

$$X_{G1} = \frac{50}{10} \cdot 0.1 = 0.5\,\mathrm{pu} \tag{1.12}$$

$$X_{G2} = \frac{50}{20} \cdot 0.15 = 0.375\,\mathrm{pu} \tag{1.13}$$

$$X_{G3} = \frac{50}{20} \cdot 0.15 = 0.375\,\mathrm{pu} \tag{1.14}$$

$$X_{1} = \frac{50}{10} \cdot 0.05 = 0.25\,\mathrm{pu} \tag{1.15}$$

$$X_{1} = \frac{50}{8} \cdot 0.04 = 0.25\,\mathrm{pu} \tag{1.16}$$

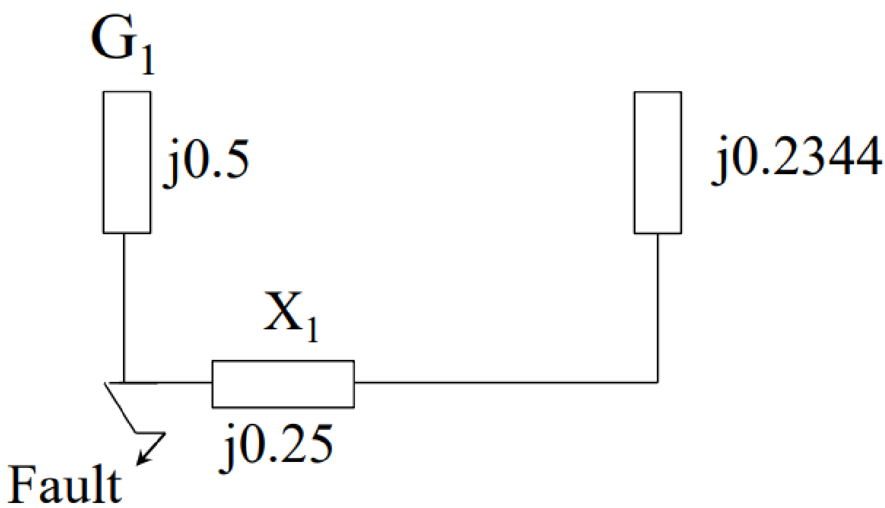

Figure 1.5: Impedance diagram circuit reduced.

$$\text{Per unit reactance} = \frac{0.5\,(0.2344 + 0.25)}{0.5 + (0.2344 + 0.25)} = j0.246 \tag{1.17}$$

$$\text{MVA Fault Level} = \frac{50 \times 10^3}{0.246} = 203.25\,\text{MVA} \tag{1.18}$$

$$\text{Fault current} = \frac{203.25 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 10\,668\,\text{A} \tag{1.19}$$

The MVA Fault Level provides information on the 'power at the fault'. The Fault Current provides information on protection e.g. circuit breakers. This is known as the symmetrical fault current.

1.2.7 Importance of MVA

- The short circuit capacity (SCC) at the busbar is the fault level of the busbar. The strength of a busbar (or the ability to maintain its voltage) is directly proportional to its SCC.
- An infinitely strong bus (or infinite bus bar) has an infinite SCC, with a zero equivalent impedance and will maintain its voltage under all conditions
- Magnitude of short circuit current is time dependent due to synchronous generators. It is initially at its largest value and decreasing to steady value. These higher fault levels tax circuit breakers (CB) adversely so that current limiting reactors are sometimes used

1.2.8 Power system symmetrical faults

- In a power system, knowing the maximum MVA Fault Level and the Fault Current that could potentially flow into a zero impedance fault is necessary in order to rate switch gear correctly
- The MVA Fault Level defines the maximum MVA that is experience when a symmetrical fault event occurs. The fault level is usually expressed in MVA (or a corresponding per-unit value)
- The maximum fault current can be calculated using the MVA Fault Level and the nominal Voltage Rating at the fault location

1.2.9 Conclusions

- The analysis show in this session has explained how impedance diagrams can be used for system analysis for 'load flows' and 'balanced faults'
- For larger or complex circuits then many more calculations are needed meaning computers are generally used to calculate load flows and faults
- Various computer programmes are available including MATLAB, Simulink Simpower Systems, PSCAD, ERACS, etc