Lecture 6: Supply Systems-Part 2

Examples for Part 1(Lecture 5)

Example 6.1

What is the percentage saving in feeder copper if the line voltage in a 2-wire d.c. system is raised from 200 volts to 400 volts for the same power transmitted over the same distance and having the same power loss ?

Solution.

Fig. 6.1 (i) shows 200 volts system, whereas Fig. 6.1(ii) shows 400 volts system. Let P be the power delivered and W be power loss in both cases. Let v1 and a1 be the volume and area of X-section for 200V system and v_2 and a_2 for that of 400 V system.

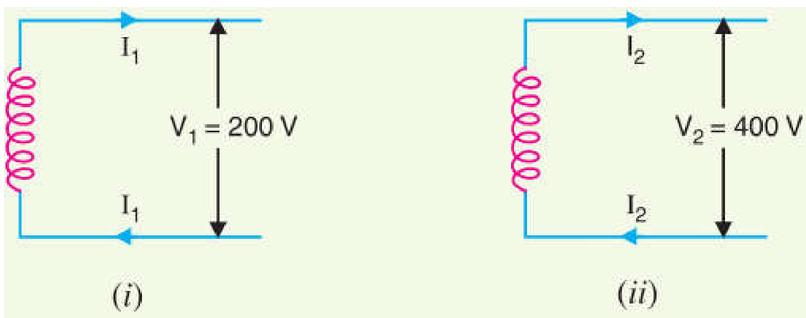

Figure 6.1

$$Now, P = V_1 I_2 = 200 I_2$$

$$And, P = V_2 I_2 = 400 I_2$$

As same power is delivered in both cases,

$$200 I_2 = 400 I_2 \; or \; I_2 = \left({}^{200}/_{400}\right) I_1 = 0.5 I_1$$

$$Power\ loss\ in\ 200\ V\ system, W_1 = 2 I_1^2 R_1$$

$$Power\ loss\ in\ 400\ V\ system, W_2 = 2 I_2^2 R_2 = 2(0.5 I_1)^2 R_2 = 0.5 I_1^2 R_2$$

As power loss in the two cases is the same,

$$W_1 = W_2$$

or

$$2 I_1^2 R_1 = 0.5 I_1^2 R_2$$

Or

$$R_2/R_1 = 2/0{\cdot}5 = 4$$

or

$$\frac{a_1}{a_2} = 4$$

$$\frac{V_1}{V_2} = 4$$

$$V_2/V_1 = 1/4 = 0.25$$

$$\%\ age\ saving\ in\ feeder\ copper = \frac{V_1 - V_2}{V_1} \times 100 = \left(\frac{V_1}{V_1} - \frac{V_2}{V_1}\right) \times 100$$

$$= (1 - 0.25) \times 100 = 75\%$$

Example 6.2

A d.c 2-wire system is to be converted into a.c. 3-phase, 3-wire system by the addition of a third conductor of the same cross-section as the two existing conductors. Calculate the percentage additional load which can now be supplied if the voltage between wires and the percentage loss in the line remain unchanged. Assume a balanced load of unity power factor.

Solution.

Fig. 6.2 (i) shows the 2-wire d.c system, whereas Fig. 6.2 (ii) shows the 3-phase, 3-wire system. Suppose V is the voltage between conductors for the two cases. Let R be the resistance per conductor in each case.

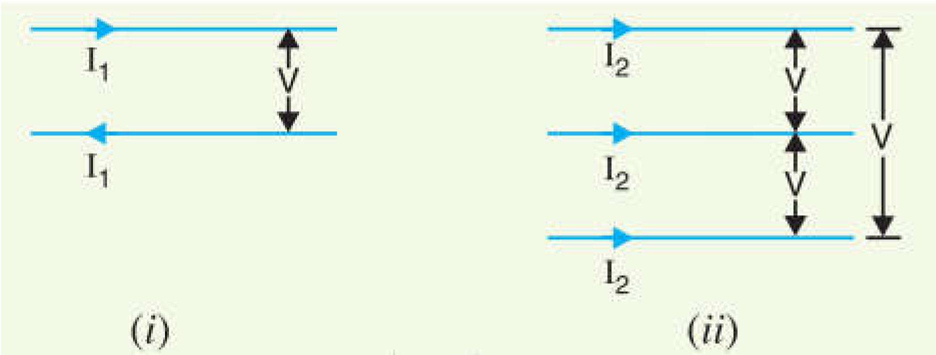

Figure 6.2

Two wire d.c system,

$$\text{Power supplied,} = P_1 = VI_1$$

$$Power\ loss, W_2 = I_1^2 R$$

$$Percentage\ power\ loss = \frac{2I_1^2R}{VI_1} \times 100$$

3-phase, 3-wire a.c. system.

$$\text{Power supplied,} = P_2 = \sqrt{3}VI_2$$

$$Power\ loss, W_2 = 3I_2^2R$$

$$Percentage\ power\ loss = \frac{3I_1^2R}{\sqrt{3}VI_2} \times 100$$

As the percentage power loss in the two cases is the same,
∴ exp. (i) = exp. (ii)

$$\frac{2I_1^2R}{VI_1} \times 100 = \frac{3I_2^2R}{\sqrt{3}VI_2} \times 100$$

$$2I_2 = \sqrt{3}I_2$$

$$I_1 = \frac{2}{\sqrt{3}}I_2$$

$$Now, \frac{P_2}{P_1} = \frac{\sqrt{3}VI_2}{VI_1} = \frac{\sqrt{3}V \times \frac{2}{\sqrt{3}}I_1}{VI_1} = 2$$

$$\therefore\ P_2 = 2P_1$$

i.e. additional power which can be supplied at unity p.f. by 3-phase, 3-wire a.c. system = 100%

6.1 Elements of a Transmission Line

For reasons associated with economy, transmission of electric power is done at high voltage by 3- phase, 3-wire overhead system. The principal elements of a high-voltage transmission line are:

i. *Conductors,* usually three for a single-circuit line and six for a double-circuit line. The usual material is aluminium reinforced with steel.
ii. *Step-up and step-down transformers,* at the sending and receiving ends respectively. The use of transformers permits power to be transmitted at high efficiency.
iii. *Line insulators,* which mechanically support the line conductors and isolate them electrically from the ground.
iv. *Support,* which are generally steel towers and provide support to the conductors.

v. *Protective devices,* such as ground wires, lightning arrestors, circuit breakers, relays etc. They ensure the satisfactory service of the transmission line.

vi. *Voltage regulating devices,* which maintain the voltage at the receiving end within permissible limits.

6.2 Economic Choice of Conductor Size

The cost of conductor material is generally a very considerable part of the total cost of a transmission line. Therefore, the determination of proper size of conductor for the line is of vital importance. The most economical area of conductor is that for which the total annual cost of transmission line is minimum*. This is known as *Kelvin's Law* after Lord Kelvin who first stated it in 1881. The total annual cost of transmission line can be divided broadly into two parts *viz.*, annual charge on capital outlay and annual cost of energy wasted in the conductor.

(*i*) *Annual charge on capital outlay.* This is on account of interest and depreciation on the capital cost of complete installation of transmission line. In case of overhead system, it will be the
annual interest and depreciation on the capital cost of conductors, supports and insulators and the cost of their erection. Now, for an overhead line, insulator cost is constant, the conductor cost is proportional to the area of X-section and the cost of supports and their erection is partly constant and
partly proportional to area of X-section of the conductor. Therefore, annual charge on an overhead†
transmission line can be expressed as:

$$Annual\ charge = P_1 + P_2 a$$

Where P_1 and P_2 are constants and a is the area of X-section of the conductor.

(*ii*) *Annual cost of energy wasted.* This is on account of energy lost mainly‡ in the conductor due to I^2R losses. Assuming a constant current in the conductor throughout the year, the energy lost
in the conductor is proportional to resistance. As resistance is inversely proportional to the area of X-section of the conductor, therefore, the energy lost in the conductor is inversely proportional to area

of X-section. Thus, the annual cost of energy wasted in an overhead transmission line can be expressed as:

Annual cost of energy wasted= P_3/a , where P_3 is a constant

Total annual cost, C= exp. (i) + exp. (ii)

$= (P1 + P_2 a) + P_3/a$

$\therefore C = P_1 + P_2 a + P_3/a$ ... (*iii*)

In exp. (*iii*), only area of X-section *a* is variable. Therefore, the total annual cost of transmission line will be minimum if differentiation of *C* w.r.t. *a* is zero *i.e.*

$$\frac{d}{da}(C) = 0$$

Or

$$\frac{d}{da}(P_1 + P_2 a + P_3/a) = 0$$

$$P_2 - \frac{P_3}{a^2} = 0$$

$$P_2 = P_3/a^2$$

$$P_2 a = \frac{P_3}{a}$$

i.e. Variable part of annual charge = Annual cost of energy wasted

Therefore Kelvin's Law can also be stated in another way *i.e. the most economical area of conductor is that for which the variable part* of annual charge is equal to the cost of energy losses per year.*

Example 6.3

A 2-conductor cable 1 km long is required to supply a constant current of 200 A throughout the year. The cost of cable including installation is KShs. (20a + 20) per metre where 'a'is the area of X-section of the conductor in cm². The cost of energy is 5Cents per kWh and interest and depreciation charges amount to 10%. Calculate the most economical conductor size. Assume resistivity of conductor material to be 1·73 μΩ cm.

$$Resistance\ of\ one\ conductor = \frac{\rho l}{a} = \frac{1.73 \times 10^{-6} \times 10^{6}}{a} = \frac{0.173}{a}\Omega$$

$$Energy\ lost\ per\ annum = \frac{2i^2 R}{1000} kWh$$

$$= \frac{2 \times (200)^2 \times 0.173 \times 8760}{1000 \times a} = \frac{121,238.4}{a} kWh$$

Annual cost of energy lost = Cost per kWh × Annual energy loss

$$Ksh \frac{5}{100} \times \frac{121238.4}{a}$$

$$= KSh\, 6062/a$$

The capital cost (variable) of the cable is given to be KSh.20 a per metre. Therefore, for 1 km length of the cable, the capital cost (variable) is KSh.20 a × 1000 = KSh.20, 000a.

Variable annual charge = Annual interest and depreciation on capital cost (variable) of cable

$$= KSh. 0.1 \times 20{,}000a$$

$$= KSh. 2000a$$

According to Kelvin's law, for most economical X-section of the conductor,
Variable annual charge = Annual cost of energy lost

$$2000a = 6062/a$$

$$a^2 = \frac{6062}{2000}$$

$$a = \sqrt{\frac{6062}{2000}} = 1.74cm^2$$

Example 6.4

The cost of a 3-phase overhead transmission line is KSh. (25000 a + 2500) per km where 'a' is the area of X-section of each conductor in cm^2. The line is supplying a load of 5 MW at 33kV and 0·8 p.f. lagging assumed to be constant throughout the year. Energy costs 4 cents per kWh and interest and depreciation total 10% per annum. Find the most economical size of the conductor. Given that specific resistance of conductor material is 10^{-}6 Ω cm.

$$Resistance\ of\ each\ conductor, R = \frac{\rho l}{a} = \frac{10^{-6} \times 10^6}{a} = \frac{0.1}{a} \Omega$$

$$Line\ current, I = \frac{P}{\sqrt{3} V cos\phi} = \frac{5 \times 10^6}{\sqrt{3} \times 33 \times 10^3 \times 0.8} = 109.35A$$

$$Energy\ lost\ per\ annum = \frac{3I^2R}{1000} kWh = \frac{3 \times (109.35)^2 \times 0.1 \times 8760}{1000 \times a} = \frac{31424}{a} kWh$$

$$Annual\ cost\ of\ energy\ lost\ = KSh.0.04 \times \frac{31424}{a} = KSh.\frac{1256.96}{a}$$

The capital cost (variable) of the cable is given to be KSh.25000 a per km length of the line.
∴ Variable annual charge = 10% of capital cost (variable) of line

$$= KSh0.1 \times 25000a = KSh2500a$$

According to Kelvin's law, for most economical X-section of the conductor,
Variable annual charge = Annual cost of energy lost

$$2500a = \frac{1256.96}{a}$$

$$a^2 = \frac{1256.96}{2500}$$

$$a = \sqrt{\frac{1256.96}{2500}} = 0.71cm^2$$

6.3 Economic Choice of Transmission Voltage

If transmission voltage is increased, the volume of conductor material required is reduced. This decreases the expenditure on the conductor material. It may appear advisable to use the highest possible transmission voltage in order to reduce the expenditure on conductors to a minimum. However, it may be remembered that as the transmission voltage is increased, the cost of insulating the conductors, cost of transformers, switchgear and other terminal apparatus also increases. Therefore, for every transmission line, there is optimum transmission voltage, beyond which there is nothing to be gained in the matter of economy. The transmission voltage for which the cost of conductors, cost of insulators, transformers, switchgear and other terminal apparatus is minimum is called *economical transmission voltage.*

The method of finding the economical transmission voltage is as follows. Power to be transmitted, generation voltage and length of transmission line are assumed to be known. We choose some standard transmission voltage and work out the following costs :
(*i*) *Transformers,* at the generating and receiving ends of transmission line. For a given power, this cost increases slowly with the increase in transmission voltage.
(*ii*) *Switchgear.* This cost also increases with the increase in transmission voltage.
(*iii*) *Lightning arrestor.* This cost increases rapidly with the increase in transmission voltage.

(*iv*) *Insulation and supports.* This cost increases sharply with the increase in transmission voltage.

(*v*) *Conductor.* This cost decreases with the increase in transmission voltage.

The sum of all above costs gives the total cost of transmission for the voltage considered. Similar calculations are made for other transmission voltages. Then, a curve is drawn for total cost of transmission against voltage as shown in Fig. 6.3. The lowest point (*P*) on the curve gives the economical transmission voltage. Thus, in the present case, *OA* is the optimum transmission voltage. This method of finding the economical transmission voltage is rarely used in practice as different costs cannot be determined with a fair degree of accuracy.

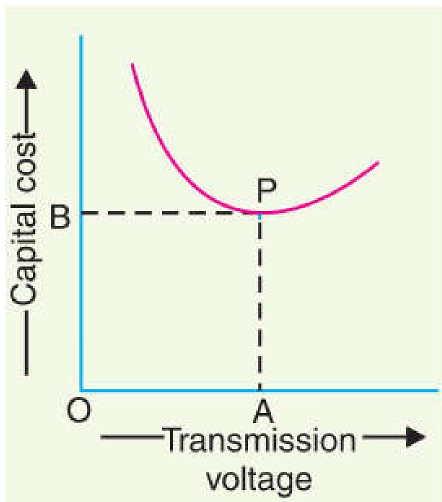

Figure 6.3

The present day trend is to follow certain empirical formulae for finding the economical transmission voltage. Thus, according to American practice, the economic voltage between lines in a 3-phase a.c. system is

$$V = 5.5\sqrt{0.62l + \frac{3P}{150}}$$

Where

V = line voltage in kV

P = maximum kW per phase to be delivered to single circuit

l = distance of transmission line in km

It may be noted here that in the above formula, power to be transmitted and distance of transmission line have been taken into account. It is because both these factors influence the economic voltage of a transmission line. This can be easily explained. If the distance of transmission line is increased, the cost of terminal apparatus is decreased, resulting in higher economic transmission voltage. Also if power to be transmitted is large, large generating and transforming units can be employed. This reduces the cost per kW of the terminal station equipment.

6.4 Requirements of Satisfactory Electric Supply

The electric power system in Kenya is 3-phase a.c. operating at a frequency of 50 Hz. The power station delivers power to consumers through its transmission and distribution systems. The power delivered must be characterized by constant or nearly constant voltage, dependability of service, balanced voltage, and efficiency so as to give minimum annual cost, sinusoidal waveform and freedom from inductive interference with telephone lines.

(*i*) Voltage regulation. A voltage variation has a large effect upon the operation of both power machinery and lights. A motor is designed to have its best characteristics at the rated voltage and consequently a voltage that is too high or too low will result in a decrease in efficiency. If the fluctuations in the voltage are sudden, these may cause the tripping of circuit breakers and consequent interruptions to service. Usually the voltage at the generator terminals, where this is done, in some cases the voltage variations at the load may be made sufficiently small by keeping the resistance and reactance of the lines and feeders low.

(*ii*) Dependability. One important requirement of electric supply is to furnish uninterrupted service. The losses which an industrial consumer sustains due to the failure of electric power supply are usually vastly greater than the actual value of the power that he would use during this period. It is on account of the expense of idle workmen and machines and other overhead charges. Interruptions to service cause irritation and are sometimes positively dangerous to life and property. For example, failure of power in hospitals, in crowded theatres and stores may lead to very grave consequences.

Therefore, it is the duty of electric supply company to keep the power system going and to furnish uninterrupted service.

(*iii*) Balanced voltage. It is very important that the polyphase voltage should be balanced. If an unbalanced polyphase voltage is supplied to a consumer operating synchronous or induction motors, it will result in a decrease in the efficiency of his machinery and also a decrease in its maximum power output. Motors called upon to deliver full load when their terminal voltages are unbalanced are liable to considerable damage due to overheating. One method of maintaining balance of voltage is by having balanced loads connected to the circuit.

(*iv*) Efficiency. The efficiency of a transmission system is not of much importance in itself. The important economic feature of the design being the layout of the system as a whole so as to perform the requisite function of generating and delivering power with a minimum overall annual cost. The annual cost can be minimized to a considerable extent by taking care of power factor of the system. It is because losses in the lines and machinery are largely determined by power factor. Therefore, it is important that consumers having loads of low power factor should be penalized by being charged at a higher rate per kWh than those who take power at high power factors. Loads of low power factor also require greater generator capacity than those of high power factor (for the same amount of power) and produce larger voltage drops in the lines and transformers.

(*v*) Frequency. The frequency of the supply system must be maintained constant. It is because a change in frequency would change the motor speed, thus interfering with the manufacturing operations.

(*vi*) Sinusoidal waveform. The alternating voltage supplied to the consumers should have a sine waveform. It is because any harmonics which might be present would have detrimental effect upon the efficiency and maximum power output of the connected machinery. Harmonics may be avoided by using generators of good design and by avoidance of high flux densities in transformers.

(*vii*) Freedom from inductive interference. Power lines running parallel to telephone lines produce electrostatic and electromagnetic field disturbances. These fields tend to cause objectionable noises and hums in the apparatus connected to communication circuits. Inductive interference with telephone lines may be avoided by limiting as much as possible the amount of zero-sequence and harmonic current and by the proper transposition of both power lines and telephone lines.