Transmission Losses in Power Sytems: an Overview

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Transmission Losses in Power Sytems: An Overview

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***Abstract*—Increase in the global population has led to a corresponding increase in demand for electric power. Electric utilities transport electric power from the generation sources to the distribution stations through transmission lines. However, the power system's transmission network experiences some losses in the process of transmitting electric power. These losses have been identified as technical and non-technical losses. However, this research paper focuses on technical losses in the transmission network. This paper aims to provide an overview of these losses, and methods for reducing such. A different perspective has also been presented in the allocation of transmission losses.**

Index Terms*—*Copper losses, core losses, non-technical losses, transformer losses, technical losses

I. INTRODUCTION

The rapid growth in population and industrialization has led to a growing demand for electrical energy. This form of energy can be regarded as the most important form of energy as it drives any society's economy. Electrical energy is usually generated from a power station, passing through large and complex transformer networks and transmitted to the end-user via transmission and distribution lines. However, a major concern of power system operators is the losses incurred during the transportation of electrical energy through transmission and distribution lines. This research paper presents an overview of some losses that occur on the transmission line in a power system. The different losses on the transmission network in a power system are broadly classified into technical and non-technical loss [1], [2], [3]. However, the focus of this research paper is the technical losses on the transmission network.

Technical losses (TL) are losses that occur naturally on the transmission network as a result of power dissipation in electrical components. These can be measured, calculated, controlled, but cannot be removed. The non-technical losses (NTL) result from fraudulent activities deliberately carried out by the end-user, contributing to over 16.6% of the total transmission losses [4]. These losses are commercial losses consisting of delivered and consumed energy that cannot be invoiced to an end-user. Due to the difficulty in quantifying and measuring NTL, these losses account for the primary source of revenue loss in transmission networks.

Underestimating losses on the transmission network can result in the under-procurement of energy while overestimating the loss factor could lead to over-procurement of resources. Generally, the transmission line losses increase the cost of operation of a power utility, invariably resulting in a higher cost of electricity production and a high cost of electricity for the end-user. According to [5], roughly 20 x 10^9 kWh of electrical energy was lost in the power system involving California's transmission and distribution lines in 2008. This is equal to about 6.9% of the energy used in California for the same year. This loss was estimated at 2.4 billion dollars at the rate of $0.1248/kWh. Ignoring the losses on the transmission network can cause a serious unbalance in the transmission network, leading to a breakdown of the network [6]. Therefore, it is important to reduce these losses to the barest minimum because of these financial and technical implications.

The rest of this research paper examines these losses broadly. Section II discusses the technical losses associated with the transmission network, section III presents a different perspective on the allocation of transmission losses, while section IV discusses techniques for reducing these losses and section V provides a conclusion to the paper.

II. TECHNICAL LOSSES

Technical losses are losses that result from auxiliary supplies, network impedance, and current flows. The sources of these losses can be attributed directly to network investments or network operations. The technical losses are usually about 22.5% of the network's total losses [7], [8]. This category of losses can be computed and controlled if the power system consists of known load quantities. The different technical losses associated with transmission losses are discussed below.

A. Corona Losses

This is a major type of power loss in the transmission lines of a power system. This type of power loss results from the ionization of air molecules surrounding the conductors on the transmission line [9]. It is generally believed that air is a good insulator, though, in a uniform electric field, the electrons and ions present in air particles are set in motion and maintain a negligible current flow. However, when the electric field's intensity at the conductor surface exceeds a certain set value, the ions gather enough energy from the collision with neutral molecules, thereby allowing them to remove an electron from the free molecules. This further ionizes the intermediate air molecules, and the new ions gather speed by the force of the electric field. Losses occur on the transmission line because the energy required in moving these ions is obtained directly from the transmission line itself.

It is important to note that there is no uniformity in the ionization rate of the air molecules; rather, this process occurs as fluctuations in the electric field around the conductor. Therefore, the name is derived from the persistent ionization around the conductor, accompanied by a glow. The color and distribution of this glow depend on the AC signal phase at any given moment in time. Positive coronas are smooth and blue, while negative coronas are red and spotty. Corona loss, therefore, reduces the power system's insulation reliability by degrading the system insulation with the possibility of a failure occurring because of dielectric breakdown. Unlike resistive losses, where the quantity of power lost is a fixed percentage of input, the percentage of power lost due to corona is a function of the signal's voltage. Corona discharge power losses are also highly dependent on weather and temperature. A pictorial representation of a corona on a transmission line is shown in Fig. 1.

Fig. 1. Corona effect in a transmission line [10]

B. Transformer Losses

Power utilities use step-up transformers to boost voltage, reduce line current and minimize power loss in the transmission lines while carrying large amounts of electric power from the generation stations to the distribution station. However, these transformers also contribute to losses on the transmission network. This research work has categorized various transformer losses into four categories, as shown in Fig. 2. These are the copper losses, core losses, dielectric loss, and stray loss. Fig. 3 represents the structure of an ideal transformer in a power system.

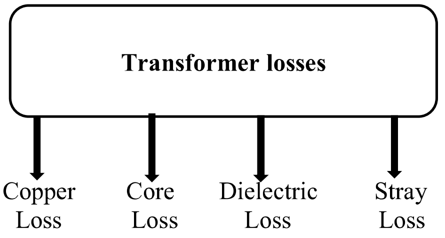

Fig. 2. Transformer losses in a power system

Copper losses usually occur in the transformer's windings, consisting of a copper (Cu) conductor, hence the name. Copper losses are also referred to as *winding loss* and are dependent on the current variations in each phase of the transformer. These losses occur because of the winding resistance (R) of the transformer and electric current (I), otherwise known as the Joule effect. This is mathematically represented as in Eqn. (1).It can be inferred that the copper losses on a transmission network increase significantly as the transformer load increases. Copper losses in the transformer can be reduced by using vacuum pressure impregnation (VPI), in addition, making the transformer windings thicker will minimize resistance.

$$P_c = RI_{rms}^2 \quad (1)$$

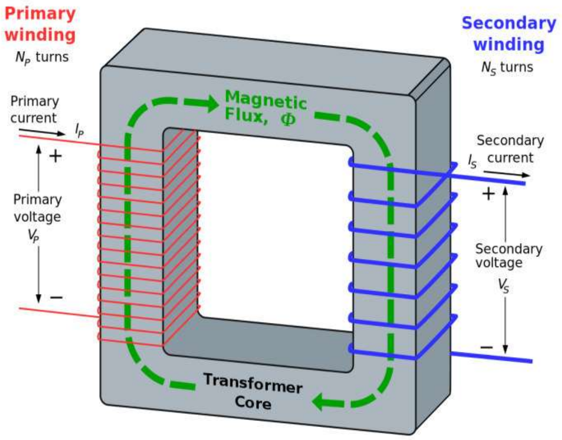

Fig. 3. Ideal transformer [11]

Core losses are sometimes referred to as *magnetizing current.* This transformer loss results from a generated alternating flux in the transformer core and depends on both the core materials' magnetic properties and the core construction. These losses consist of two-loss types- Eddy current loss (P_e) and hysteresis loss (P_h). At constant frequency, the core losses depend on variation in voltage. Assuming the voltage variation on the transformers occurs within a narrow range, the core losses are assumed constant while the transformer is energized [9]. These two losses are dependent on the maximum flux density (B_{max}) of the magnetic field and frequency (f). Eddy current losses in the transformer are caused by a change in the transformer core's magnetic field, while hysteresis losses result from the magnetic field's motion. Both losses can be minimized by the use of thin core lamination and silicon materials, respectively.

The core loss in the transformer is mathematically given as

$$P_i = P_e + P_h \qquad (2)$$

where,

$$P_e = K_e B^2 f^2 t^2 V \quad (3)$$

and

$$P_h = K\eta B^{1.6} f V \quad (4)$$

K_e is a coefficient constant whose value depends on the volume and resistivity of the core material, $K\eta$ is a constant whose value depends on the material of the magnetic core, B is the flux density, f is the frequency, t is the lamination material thickness and V is the volume of the material, respectively.

A leakage causes stray losses in the magnetic flux, produced in the transformer's metallic part such as the transformer winding and transformer tank, producing eddy current losses in them. Thus, they occur all around the transformer rather than a definite place, hence the name 'stray'. Also, the leakage flux is directly proportional to the load current, unlike the mutual flux proportional to the applied voltage. Hence, this loss is referred to as a 'stray load' loss. The less leakage in transformer current, the more negligible the stray losses become.

Dielectric losses are a result of deterioration in the transformer oil or insulation capacity of the transformer. The decline of the transformer oil or damaged solid insulation affects the transformer efficiency. This loss can be minimized by ensuring the insulation capacity, and quality is maintained and regular testing of the transformer oil. Just like the stray losses, dielectric losses are negligible and can be neglected.

Copper losses and core losses are the most common types of losses experienced by the transformer. Therefore, the total transformer loss in a transmission network is a combination of the copper loss and core loss, calculated as

$$P = P_c + P_i \quad (5)$$

C. Line Losses

Electric power is usually transmitted over a long-distance using power lines. Depending on the model adopted, these transmission lines can be long, medium, or short. A transmission line that is less than 50 miles (80km) is classified as a short transmission line; medium transmission lines are lines that are between 50 miles (80km) and 150 miles (241km), while transmission lines longer than 150 miles are generally classified as long transmission lines. The longer the transmission line, the more the likelihood of increased losses on the line. The equivalent circuits of the short and medium-length transmission lines are shown in Figs. 4 and 5, assuming a balanced condition. The short and medium-length transmission lines are modeled using a lumped-parameter model while the long transmission line is modeled, bearing in mind that the parameters of the line must be uniformly distributed along the line.

Most of the loss on the transmission line is energy lost as heat in the conductors. Most losses on the transmission line occur because of the resistance of the conductor against current flow. This causes heat to be produced in the conductor, thereby increasing the temperature of the conductor. The increase in temperature of the conductor invariably leads to increased conductor resistance and, consequently, a significant increase in power losses [12].

Reactive currents also play a very significant role in the power losses on the transmission line. Increased reactive currents on the transmission line imply an increase in the reactive power, leading to a decrease in the power factor. A lower power factor on the transmission line results in higher losses. Solving this losses problem, power utilities usually add capacitor banks, reactors, or other devices to compensate for reactive power, reducing power transmission losses[13].

D. System Parameters

When current flows in a transmission line, the transmission line's characteristics are explained as a function of the magnetic and electric field interactions. Circuit elements or parameters represent the phenomena that arise from these interactions. Combining circuit elements, an equivalent circuit of the transmission line can be formed and used in determining some of the losses on a transmission line.

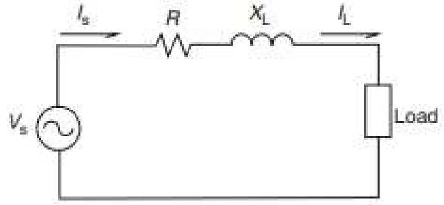

Fig. 4. Equivalent circuit of a short length transmission line

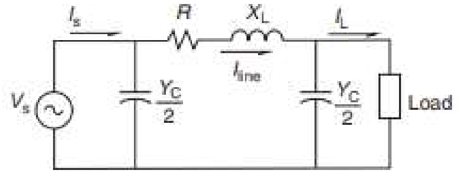

Fig. 5. Equivalent circuit of a medium length transmission line

Shunt conductance is associated with dielectric losses. The conductance from line to line or a line to the ground represents losses that occur because of leakage current at the cable insulation and the insulators between overhead lines. Factors such as atmospheric pressure affect conductance; therefore, the line's conductance is not uniformly distributed along the transmission line, making it impossible to measure the conductance values accurately. Fortunately, the leakage in the overhead lines is negligible, even in detailed transient analysis. This makes it possible for this parameter to be completely neglected.

The main source of losses in the transmission system is the resistance of the conductors. For certain parts of the transmission line, power is dissipated as heat as the current tries to overcome the line's resistance. It is directly proportional to the square of the rms current traveling through the line. The losses due to the line resistance can be significantly minimized by raising the transmission voltage level. The transmission line's resistance value will change as the line dissipates power in the form of heat energy.

The capacitive reactance of a transmission line comes about because of the interaction between the electric fields from conductor to conductor and from conductor to ground. The alternating voltages transmitted on the conductors cause the charge present at any point along the line to increase and decrease with the instantaneous changes in the voltages between conductors or the conductors and ground[14]. This flow of charge is known as the charging current and is present even when an open circuit terminates the transmission line [14].

Alternating magnetic fields accompany the alternating currents present in a transmission system. The interaction of these magnetic fields between conductors in relative proximity creates a flux linkage. These changing magnetic fields in the transmission line induce voltages in parallel conductors equal to the time rate of change of the line's flux linkages. This voltage is also proportional to the time rate of change of the current flowing in the line.

Due to the relative positioning of the transmission lines, the mutual coupling will cause voltages to be induced. The induced voltages add with the line voltages and cause an unbalance in the phases. Looking at only the simple resistive losses in the circuit and recalling that the power loss is directly proportional to the square of the magnitude of the current flowing in the line, it is easy to see that the losses in one line will increase significantly more than the reduction of losses in the other lines. It is also important to note that the line reactance increases with mutual coupling, contributing significantly to the transmission network's line losses.

E. Skin Effect

The internal flux of a conductor produces a concept referred to as the skin effect. This flux consists of flux lines that are circular and concentrated around the conductor surface, resulting in flux lines that link only a portion of the cross-section of the conductor. Fig. 6 illustrates this concept.

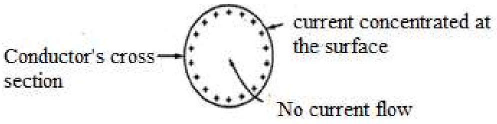

Fig. 6. Skin effect on a transmission line

This concept is negligible in short transmission lines, but with increased use of long transmission lines, the skin effect increases considerably. Therefore, the conductor's central cross-sections have larger total flux linkages than the area closer to the outside of the conductor. This means that a higher voltage is induced longitudinally inside of the conductor than on the outside. As a result, a larger inductive reactance is induced into the core compared to the conductor's outer sections. The high value of reactance in the inner section results in an un-uniform distribution of current, forcing the bulk of the current to flow through the outer surface or skin, giving rise to the phenomena called skin effect in transmission lines. The skin effect effectively reduces the cross-section of the conductor, thereby increasing the resistance of the conductor. The skin effect on a transmission line depends on factors such as the shape of the conductor, the operational frequency, the type of material used, and the conductors' diameter.

III. ALLOCATION OF TRANSMISSION LOSSES

Allocating transmission losses has always been a challenging and contentious discussion in power system analysis. There have been various proposals and discussions around this topic in literature as presented in [6], [15], [16], [17]. As previously stated in Section II, technical losses in transmission networks are due to load quantities. However, load quantities are not solely responsible for transmission losses in the power system. Two important components that have been often overlooked in discussions around transmission losses are losses contributed by the generators [18] and the transmission network itself. Therefore, it is not accurate to allocate all technical losses in a transmission network by assuming that such losses are solely caused by loads. Therefore, this research paper has further grouped the various technical losses discussed in Section II into *load, generator, and network losses* and discussed below.

Load losses on the transmission line in a power system can be determined by considering the impact of the load on the total current flowing through the line. The contribution of load to the current flowing through a line can be determined by projecting the partial current flow resulting from the presence of the load on the line in the direction of total current. Since current flow is necessary for power transmission to load, load losses cannot be avoided on the transmission network. The associated load loss can therefore be calculated as a fraction of the loss on the transmission line. This fraction is a ratio of the load contributed to the total current [19]. Assuming that current flowing through a branch is i_a, and total loss in the branch is ΔP_a, the loss ΔP_{aL}, from the load causes a partial flow of current i_{aL} through the line. Therefore,the associated loss ΔP_{aL} is calculated as shown in (6)

$$\Delta \mathrm{P}_{\mathrm{aL}} = \frac{\mathrm{i}_{\mathrm{aL}} \cdot \mathrm{i}_{\mathrm{a}}}{|\mathrm{i}_{\mathrm{a}}|^2} \cdot \Delta \mathrm{P}_{\mathrm{a}} \qquad (6)$$

where, $\mathrm{i}_{\mathrm{aL}} \cdot \mathrm{i}_{\mathrm{a}}$ is a dot vector product.

Unlike load losses, generator losses on the transmission network can be prevented if there is an equal magnitude between the generator voltages, and the phase angle between them is the same. However, it is important to state that this condition is practically impossible as a result of the active and reactive power limits of each generator, satisfying load demand at the same time and flat generator voltages.

In a transmission network, the meshed transmission lines form conducting paths between generators of different voltages, leading to currents circulating between the different generators in the network. The circulating currents will invariably lead to additional losses on the network. The generator can perform a dual role of a sink or source for the circulating currents. Irrespective of the role of the generator, the associated loss from the circulating current is equally shared between the source and sink. The different steps to be taken to allocate this loss has been clearly outlined by the authors in [19].

Network losses can be regarded as being dependent on the transmission network itself. Such losses arise from network control measures such as shunt capacitors, phase-shifting transformers, etc. If this loss increases the overall loss of the network, then it can be regarded as a positive loss. However, if this loss reduces the total loss of the network, then it can be regarded as a negative loss. The network loss constitutes a minute percentage of the total losses on a transmission network. It can therefore be allocated to the independent system operator (ISO).Allocation of this loss can also be done by introducing a scaling factor K, to scale the losses on the loads and generators to account for the network loss.K can be calculated as shown in Eqn. (7).

$$K = \frac{\Delta P_T}{\Delta P_L + \Delta P_c} \qquad (7)$$

where ΔP_Trepresents the total losses on the transmission line, ΔP_L and ΔP_c represents the load losses and the circulating current losses, respectively.

IV. REDUCTION OF TECHNICAL LOSSESINTRANSMISSION NETWORKS

Technical losses in transmission networks cannot be eliminated, however, certain measures can be put in place to mitigate or reduce these losses and their effect on the transmission network. Several methods have been proposed in the literature for reducing technical losses on transmission networks. This section outlines and discusses some of the measures which can be put in place to mitigate the impact of these losses on the transmission network.

Configuring a transmission network is a very complex but important process in electric power systems planning. If poorly done, can lead to a low power factor, an increase in power loss, and possibly a poor voltage profile. The reconfiguration of a transmission network has been identified as a very important measure that can help in the reduction or mitigation of these technical losses on the network. The authors in [20] presented a comprehensive review of various techniques applied in network reconfiguration.

The objective of reconfiguring the network is to achieve a desirable combination of loads, sources, transmission lines, and to build a stabilized skeleton network that prepares for load pickup [21], thereby minimizing the active power losses on the network and improving the voltage profile thereby improving system performance [22]. This can also be regarded as a restoration process on the network which entails a multi-time-step process. The network configuration of the transmission network determines the losses on the network with regards to the transportation of electricity over a distance.

A change in demand on the network may have implications on the network in a scenario where the network is not optimally configured for the demand. Therefore, reconfiguring the network for the provision of a more direct and shorter path to where demand is higher can lead to a reduction in losses. Network reconfiguration is a more common technique due to its cost-effectiveness [23].

Transmission losses on the network can also be minimized by the addition of a flexible ac transmission system (FACTS) device at various points on the network closest to the source of reactive load. The application of FACTS devices on transmission networks not only minimizes losses on the network but improves voltage profile and enhances power flow. There is an increased transient stability limit which invariably improves the dynamic security of the transmission network thereby reducing the possibility of blackouts which are a product of cascading outages.

In [24], the authors demonstrated the effectiveness of FACTS devices as a method for reducing losses on a transmission network. Some equipment and end-use loads on the network are naturally inductive, causing the grid to supply reactive power as a result of the lagging power factor. The injection of reactive power leads to an increase in total line current, thereby contributing additional losses in the system. The placement of FACTS devices at or near the point of reactive power load ultimately helps in improving the lagging power factor thereby increasing available capacity in the lines by reducing the line current. A very critical factor to consider in the use of FACTS devices for loss reduction or minimization in transmission systems is the optimal placement of such devices. The choice of location for the FACTS device on the transmission network, as well as modeling, is important. Various optimization techniques have been proposed for the optimal placement of FACTS devices on a transmission network for loss reduction. These are well discussed in [25, 26].

In the technical report presented in[27] to assess transmission losses and how to reduce losses on the bulk transmission system of the State of New York, the use of software technology such as Optimal Power Flow (OPF) software technology has also been proposed as a solution to reducing losses on the transmission line. Such technology can monitor and send reactive power management signals in real-time to transmission facilities that have the potential to reduce transmission losses. A major benefit of such technology to utilities is its cost-effectiveness, especially during non-peak hours. In addition to power flow analysis by software technology, it is possible to model improvements on the transmission system to determine where a reduction on the transmission system can be achieved.

V. CONCLUSION

The transmission network plays a critical role in delivering electricity to the end-user from generation. Transmission lines are used in delivering this energy from the point of generation to the distribution stations. However, the transmission network in the power system suffers from some losses. This research paper has discussed these losses, categorized them as technical and non-technical losses. Technical losses are losses that result from auxiliary supplies, network impedance, and current flows. The sources of these losses can be attributed directly to network investments or network operations. Technical losses can be quantified, calculated, and controlled. The different technical losses associated with the transmission of electric power have been explained. The non –technical losses are losses incurred because of fraudulent activities deliberately carried out by the end-user. However, this research work has not discussed the non-technical losses.

Technical losses on the transmission network cannot be eliminated, however, these can be reduced as much as possible thereby improving the reliability of the system. Two main techniques used in loss reduction on transmission systems have been discussed. Also, the use of software technology by utilities can greatly reduce losses on the transmission network.

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