Application of Trilemma Concept to minimize Transmission and Distribution Losses in Nigeria: An Overview.

Terab Malam Ali[1], Babangida Modu[2], Umar Ali Benisheikh[2] and Falmata Alhaji Mai[3]

[1] Department of Computer Engineering Technology
[3] Department of Mathematics and Statistics
Ramat Polytechnic Maiduguri, Borno State
[2] Department of Electrical and Electronics Engineering
University of Maiduguri, Borno State
Correspondence e-mail: terabkukawa@yahoo.com

Abstract

Electrical power is the backbone of socio-economic and educational development of a nation. According to the UNEP report 2017, there are 1.7 to 2 billion people who lacked access to electricity across the world. The major indicator of human development is the per capita electricity consumption measured as functions of access to electricity by a population of a country. The objectives of energy trilemma review is to address the trade-offs and interdependencies of the three components of the trilemma triangle as well as the application of the performance indicators in arriving at optimal decision on energy management system in Nigeria. The electrical transmission and distribution sub sectors are the most prone sections to power losses. The major reasons attributed to losses in this power sections is the resistance of conductor against the flow of electrons. The increase in temperature of conductors is as a result of this opposition to the electrical current flow; hence the high resistance also increases the losses. The relative percentages of losses are calculated based on internationally accepted tolerances. The acquisition and implementation of new paradigm technologies are imperative for optical power flow analysis. Some future perspectives on power sector improvement in Nigeria is also outlined for consideration by stakeholders.

Keywords: **Trilemma, Power Losses, Energy Security, Energy Equity, Environmental Sustainability**

I. Introduction

Nigeria is a vast country with 923,768 square kilometers size and rich in minerals and hydrocarbon deposits. The country borders Benin republic to the west, Cameroun to the east, Niger to the North, Chad to the North East and Atlantic Ocean to the south. The cities and rural are either connected to the National grid or islanded grid. According to the authors in [4] 85 million Nigerians lack access to the electricity grid, this represents more than 40% of the entire population and makes Nigeria the largest electricity access deficit country in the world(Otobo, Hartungi, Ibraheem, & Estebsari, 2023).

The major sources of electricity in the country includes Hydropower and Thermal plant. The main source of electricity generation is from fossil fuels which accounts for over 86% of the total power generation of the country. Despite the abundance sources of renewable energy such as solar, wind, biomass and large hydropower potential, the country still lacked the full exploration of these resources. The present generation capacity of around 4,000 MW is grossly inadequate to meet the growing population of over 200 million. The major challenges in the power sector includes pervasive corruption(Ole, 2020), vandalism, shortage of gas supply, aging transmission infrastructures and above all poor planning and management(Arowolo & Perez, 2020).

Electricity is the bedrock of socio-economic, infrastructural and educational development of a nation. According to the United Nations Environmental Program (UNEP) report 2017, there are 1.7 to 2 billion people who lack access to electricity across the world (Attia, El Sehiemy, & Hasanien, 2018). Unfortunately over 60% of this population lives in the rural areas in developing and underdeveloped countries. The major indicator of human development is the access to affordable, adequate and reliable energy (Olatomiwa, Mekhilef, Huda, & Ohunakin, 2015). The actual reason for lack of access is largely attributed to poor terrain, insufficient investment capital and in some cases, inadequate political commitment from leaders (Akunne & Ibrahim, 2021). According to the World Bank report on ease of doing business released in 2021, Nigeria is ranked 171 out of 190 countries surveyed which indicates lack of access to power for private sector investment.

The Nigeria Power sector reform was outlined between the year 2010 and 2013 but it is widely condemned as futile venture by most energy analyst. The failure of the reform is evidenced by a myriad of seemingly insurmountable economic, institutional, technical, financial and socio-political challenges exacerbated by the recent global macroeconomic crisis(Aliyu, Ramli, & Saleh, 2013). Despite successive Government efforts to tackle the power sector problem, many businesses and organizations still relay on alternative power sources such as generators(Roy, Iwuamadi, & Ibrahim, 2020). This situation has greatly affected the cost of materials and charges for services in addition to high carbon emission(Yetano Roche et al., 2020). According to Wikipedia 2023, only 30% of these renewables were utilized. For instance the average annual diurnal solar irradiance ranges from 3.5 kWh/m2/day at the coastal areas to an appreciable 7.0 kWh/m2/day which translates to 9 hours per day in the far northern states. In the same vain, according NIMET report 2020 wind speed at altitude of 10 m to 50 m by a cup-generator anemometer ranges from 4.49 m/s in the southern region to 6.10 m/s in the northern region. The yearly solar irradiance across the country is very encouraging for massive investment drive in solar renewable energy as shown in table 1.

Table 1: Yearly solar irradiances kWh/m2 (Modified from Global horizontal radiation).

Zone	Solar Irradiance kWh/m2/d	Average Time h/d	States
1	5.7 – 6.5	6.0	Borno, Yobe, Bauchi, Gombe, Katsina, Kano, Kaduna and Plateau
2	5.0 -5.7	5.5	Sokoto, Kebbi, Zamfara, Nasarawa, Abuja, Niger, Kwara and Taraba
3	<5.0	<5.0	Oyo, Osun, Ekiti, Benue, Rivers, Enugu and Lagos.

Trilemma in philosophy is a choice between three unfavorable options. When referred to energy security, equity and environmental sustainability, trilemma ensures achieving all the three goals simultaneously without trading any component at the expense of the other. Energy trilemma concept describes how the three requirements that should be achieved and cannot be independently considered as shown in figure 2. The energy trilemma, described by World Energy Council (WEC) as the balance between energy security (reliability), energy fairness (equity), and environmental conservation (sustainability), which exemplifies the basic problems of the global transition of energy (Syafrianto, Banjar-Nahor, Rahmani, Hadi, & Hariyanto, 2020).

The security component encompasses the potential to satisfy present and future demands of energy, as well as the capacity to curtail and recover from system outages and shocks, which includes dependability and resiliency. The equity components assess the system's ability to supply affordable, qualitative, and adequate energy. In addition, the environment sustainability component should provide the ability of the system to minimize and prevent the effects of greenhouse emission (GHG) and environmental degradation.

Furthermore, one of the essential components of power system is the power generation planning to meet the power network load demand. The transmission lines connects the generation sources to the substation for subsequent distribution to load centers(Bhatti et al., 2015). However, the transmission and distribution of electricity are prone to losses as function of distance and diameter of conductors used.

Therefore the objectives of this paper is to;

1. Provide an overview of the Nigerian power sector challenges especially as its regards to energy security, energy access and environmental sustainability using the energy trilemma concept.
2. Recommend some future perspectives on how to implement the trilemma concept in the Nigerian power sector supply and demand value chain to realize SDG goal 7.

II. Overview of Nigerians Generation, Distribution and Transmission Capacity

The generation companies (GENCOS) are Geregu Power Plc with an installed generation capacity 414 MW, Ughelli Power Plc with installed generation capacity 900 MW, Afam Power Plc with 726 MW installed capacity, Sapele Power Plc with 1020 MW thermal capacity, Kainji (Jebba) Hydro Power Plc with 1300 MW hydro capacity and Shiroro Hydropower Plc with 600 MW capacity as well as Egbin Power Plant with 1320 MW capacity in Lagos.

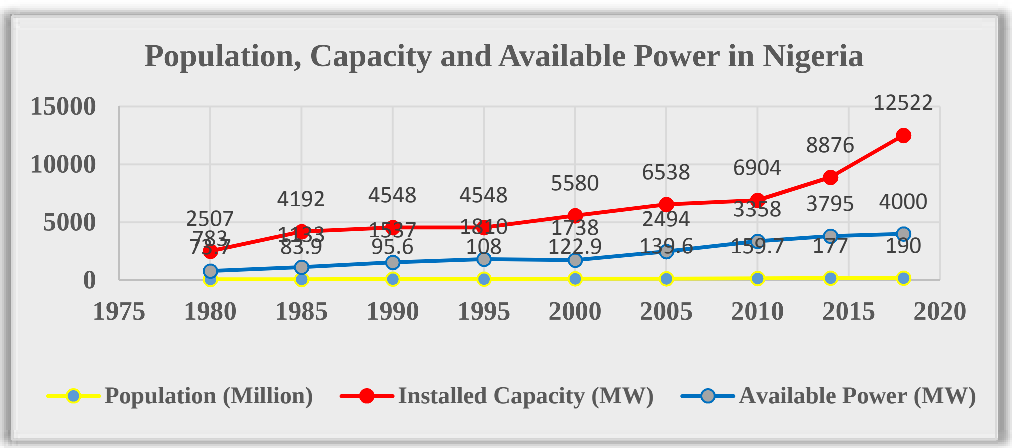

Figure 1: Population, Capacity and Available Power in Nigeria between 1980-2018.

Figure 1 above shows the increase in Nigerian population and installed capacity from 1980 to 2018. The peak installed capacity of 12,522 MW was achieved in 2018 by the National Integrated Power Program (NIPP) (Usman, Abbasoglu, Ersoy, & Fahrioglu, 2015).

The distribution companies (DISCOS) are Abuja Electricity Distribution Company (AEDC), Benin Electricity Distribution Company (BEDC), Enugu Electricity Distribution Company (EEDC), Eko Electricity Distribution Company (EKEDC), Ibadan Electricity Distribution Company (IBEDC), Ikeja Electricity Distribution Company (IKEDC) later renamed Ikeja Electric, Jos Electricity Distribution Company (JEDC), Kaduna Electricity Distribution Company (KAEDC), Kano Electricity Distribution Company (KEDC), Port Harcourt Electricity Distribution Company (PHEDC) and Yola Electricity Distribution Company (YEDC) (Ayamolowo, Buraimoh, Salau, & Dada, 2019).

The transmission facilities are under the supervision and control of Transmission Company of Nigeria (TCN). Geregu II with 434 MW transmission line, Sapele with 450 MW line, Alaoji with 107 MW, Olorunsogo II with 2 750 MW line, Omotosho II with 500 MW, Omoku with 250 MW line, Ihovbor with 450 MW line, Calabar with 561 MW line, Egbema with 338 MW line and Gbarain with 225 MW Power Stations. As at October 2018 (8 out of the 10 plants) were already connected to the National Grid [6]. Figure 2 shows the generated and transmitted power in MW within the period under review in 2018 and its available MW from the GENCOS. This scenario has been the same over years where available power cannot be transmitted due to inadequate transmission facilities.

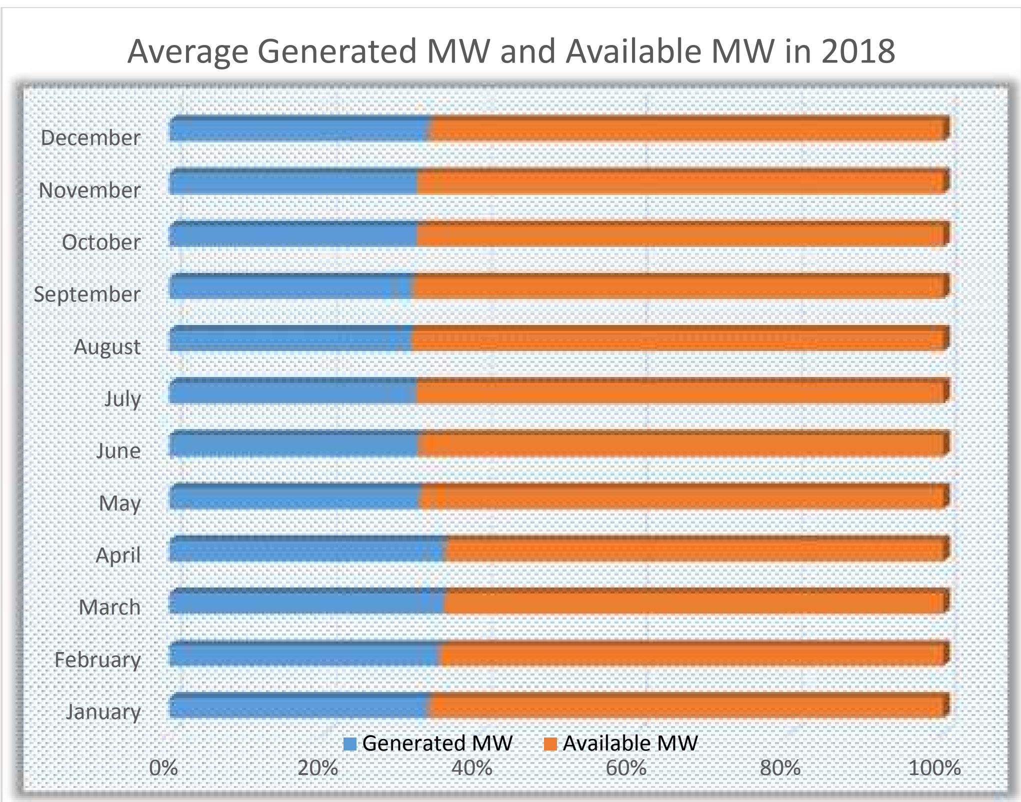

Figure 2: Average Generated MW and Available MW of Nigeria in 2018 (Modified from [6]).

III. Application of Energy Trilemma to Electricity Utility

The first component of the trilemma concept is the energy security as shown in figure 3. The term is mostly subjective to discipline, individuals and nations depending on the perspective of the researchers. However, reliability, adequacy and resiliency of energy generation, transmission and distribution stands out more acceptable in most literatures(Yu, Fang, Pan, & Jia, 2023). The resilience component of energy security defines the ability of the energy network to regain normalcy when subjected to disruptions as a result of natural disasters, inter and intra-country crisis.

The concept of energy access, energy poverty and energy equity is the second component. This term is continuously argued with different scholars trying to proper comprehensive definitions. For instance the authors reported 'energy access' as affordable price and connection to the grid. However, the authors in Aliyu et al., emphasized more on the dynamic nature of access which includes connection, minimum consumption level and increasing electricity tariffs over time as a result of consumer preferences. In the opinion of this authors, the terms affordability, adequacy and basic needs are subjective to the consumption characteristics and income level of the target groups(Gibellato, Ballestra, Fiano, Graziano, & Gregori, 2023). Therefore, it is ideal to include the dynamic nature of the definition of energy access to capture the target group preferences and economic status.

The third component of the trilemma triangle provides for deliberate environmental protection measures to ensure environmental sustainability. Principally, human economic advancement is interwoven with quality of energy management system. Consequently, land expansion for development, power plant constructions, and transmission infrastructures can lead to deforestation(Tol, 2023), land over grazing and GHG emissions. Consequently, the ultimate consequences of such uncontrolled efforts may cause global climate change in the form of flooding, water receding, global warming and several human survival threatening disasters(He et al., 2023). The paradigm transition to energy trilemma is the ultimate means to ensure economic prosperity, safer global existence and sustainable environment(Lee et al., 2023).

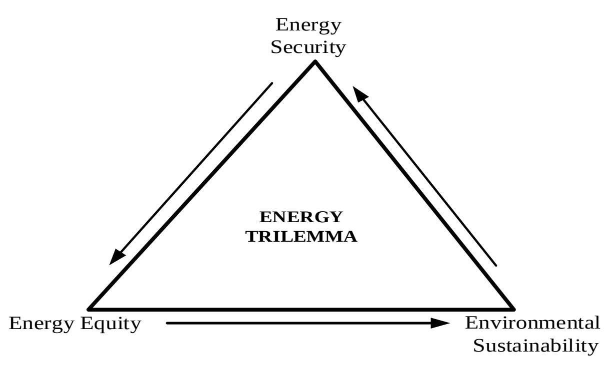

Figure 3: The Energy Trilemma Triangle

The comparative improvement in trilemma index over the last two decades shows significant breakthrough in over 90% of the 119 countries surveyed by Khan et al. The top three countries in the overall trilemma index as at 2019 were Switzerland, Sweden and Denmark. However, for the energy security and environmental sustainability component of the trilemma dimensions, Luxembourg, Bahrain, Qatar and also Switzerland, Denmark and Sweden are the leading top threes respectively(Khan, Zakari, Dagar, & Singh, 2022). In terms of the continental leading countries, Mauritius is ahead in Africa while Uruguay and Canada seems to be ahead in Latin America and Caribbean and North America respectively(Bonafé, 2022). Figure 4 shows the sub components of the Energy Trilemma Index as outlined by the World Energy Council report 2019.

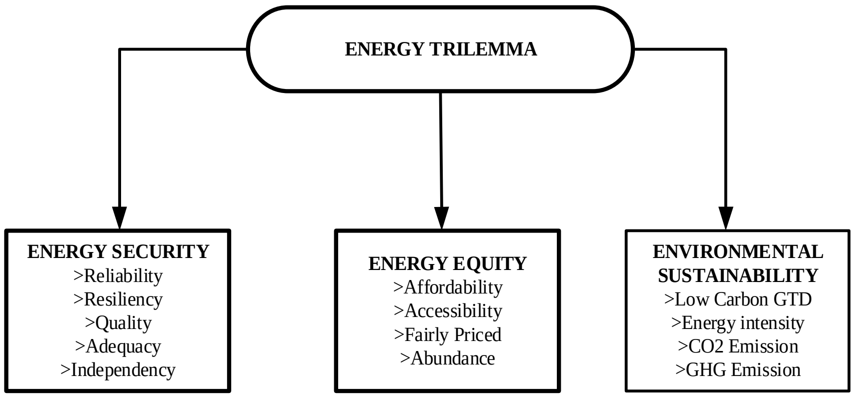

Figure 4: Sub Components of Energy Trilemma Concept

The objectives of energy trilemma review most be seen to address the trade-offs and interdependencies of the three components as well as the application of the performance indicators to in arriving at political decision on optimal energy management system in Nigeria. As shown in Table 2, the world energy trilemma structure composed of energy security 30%, energy equity is graded 30% and environmental sustainability is rated on 30% and 40 points ahead of security and equity which were pegged at 30 each. The remaining 10% was assigned to reflect the socio economic and administrative circumstances of different countries.

Table 2: World energy trilemma index(Abdelhak Chibani et al.) (Modified from WEC 2019 Report)

Energy Trilemma Criterion	World Energy Council Indicator		Indicator for Electricity Utility	
❖ Energy Security (30%)	*Diversity of primary Energy supply	6%	▪ Voltage violations	20
	*Import Dependence	6%		
	*Diversity of Electricity Generation	6%	▪ Loading violations	10
	*Energy Storage	6%		
	*System stability &recovery capacity	6%		
	*Access to Electricity	6%	▪ Affordable LCOE	21
	*Access to Clean Cooking	6%		
	*Access to modern Energy	6%		

❖ Energy Equity (30%)			▪ Decrease Losses	9
	*Electricity Prices	3%		
	*Gasoline and Diesel Prices	3%		
	*Natural Gas Prices	3%		
	*Affordability of electricity for residents	3%		
❖ Environmental Sustainability (30%)	*Final Energy Intensity	5%	▪ CO_2 Intensity	40
	*Efficiency of Power Generation and Transmission and Distribution	4%		
	*Low Carbon Electricity Generation	5%		
	*GHG Emissions trend	3%		
	*CO_2 Emissions Intensity	2%		
	*CO_2 Emission per Capita	2%		
	*CH4 Emissions per Capita	1%		
	*PM2.5 mean annual exposure	4%		
	*PM10 mean annual exposure	4%		

IV. Description of Electrical Losses

The electrical transmission and distribution sub sectors are the prone sections of losses. The major reasons attributed to losses in this power sections is the resistance of conductor against the flow of electrons. The increase in temperature of conductors is as a result of this opposition to the electrical current flow, hence the high resistance also increases the losses(Phyu, Lin, & Moe, 2018). This is called the ohmic power loss which is the most common in transmission and distribution lines. This mean it is virtually impossible to eliminate transmission or distribution losses, however, with proper power planning, it can be reduced to the barest minimum. The distribution link is weakest in the power system in terms of losses(Ebeed, Kamel, & Jurado, 2018). Distribution networks accounts for over 50% of the total losses while transmission provides only about 17% of the total losses. Generally, losses can be classified as technical and non-technical losses.

Technical Losses

The technical losses are majorly due to the energy dissipated in the conductors, equipment used for transmission line transformer, sub-transmission line, and distribution line. Technical losses are usually pegged at 22.5% (May, Yeap, & Ukil, 2016). Some of the reasons of technical losses are:

i. Lengthy distribution lines
ii. Inadequate size of conductors
iii. Installation of distribution transformers far from load centres

iv. Unequal load distribution among the phases
v. Loss of power and leakages
vi. Overloading of lines
vii. Abnormal operating conditions

However, some losses due to corona effects, leakage current, dielectric and open-circuit losses as well as losses due to control and measuring elements also account for significant percentage in the distribution lines(Tushar, Zeineddine, & Assi, 2017).

Non-Technical losses

Main areas of non-technical losses in the distribution feeders which are due to energy theft includes un-metered supply, arranged false meters, meter tampering and by-pass and faulty meters. The remedy of such scenarios are political and to a greater extent enforcement of existing NERC regulations on energy thefts(Sayed & Massoud, 2019).

How to minimize losses

According to the work carried out by the New York utilities, EPRI, and SAIC, as well as reviews of other industry studies, electric losses can be reduced by system improvements both in the transmission and distribution systems. Generic or case-specific cost/benefit analysis is required to justify the required expenditure for these system improvements.

Transmission Systems Losses Reduction

1. Optimization of existing controls for transformer taps, generator voltages, and switched shunt capacitor banks reduces current flow and minimizes losses.
2. The addition of shunt capacitor banks, fixed and switched, at points on the system closest to the reactive load source reduces current flow and minimizes losses.

Distribution Systems Losses Reduction

1. Phase balancing reduces line and neutral conductor losses.
2. Distribution capacitor banks on the feeders to improve the feeder power factor reduce line losses.
3. Capacitor banks at or near the substation improve the station power factor caused by the substation power transformer VAR requirement, measured at the high side of the power transformer, and reduce load losses in the substation transformer.
4. Use of life-cycle evaluation for equipment sizing (initial installation of distribution transformers and conductors) reduces transformer core and coil losses.

V. Impact of New Technology on Losses

The electric system grid is dynamic in nature, with constantly evolving technology improvements and enhancements(Addisu, Salau, & Takele, 2021). One consideration for power systems is the impact on losses from technological advancements. The following discussion describes the impact that new technologies could have on losses in transmission and distribution systems(Dastgeer & Gelani, 2017).

Advanced Metering

The data from advanced metering becomes integrated into the utility's infrastructure, at both the feeder and substation level, as well as the customer level, the load data can be directly assigned to the computer simulation model. In addition, hourly data, including kW and kvar, can be used to calculate energy and peak system losses. This method can produce more precise results by eliminating estimations of load allocation and providing added granularity in the results.

High-Voltage Direct Current (HVDC) Transmission

An emerging trend being considered is high-voltage direct current (HVDC) lines because of some of the advantages in efficiency. According to an ABB study, HVDC lines provide 25 percent lower line losses, two to five times the capacity of AC lines at similar voltages, and the ability to precisely control the flow of power. Historically, the costs have been too high for most transmission operators to consider HVDC as an option, except in a few long-distance applications. However, with technological improvements and more economical options becoming available, HVDC may be considered more feasible in the near future in Nigeria.

Gas-Insulated Substations

Gas-insulated substations are a possible solution to help reduce losses. Typical substations occupy large tracts of land and are located outside of dense load areas. As a result, lower-voltage lines from substations can go quite a distance before reaching load centres, which increases losses. Gas-insulated substations are encapsulated, with all equipment inside a metal housing, and can be contained in a basement or building close to the load centre, which would help in the reduction of losses.

VI. Mathematical Modelling of Power Losses

The increase in resistance to current flow by a conductor rises the temperature and at the same increases line losses in both transmission and distribution lines. Ohmic power loss is the major source of losses in T and D lines.

Therefore, the ohmic power loss is given as

$$Lohmic = I^2R \;\; KW/Km/Phase \quad \ldots 1$$

Where

I indicates current along the conductor
R indicates the resistance of the conductor

The formation of corona in transmission line is associated with loss of power which affects the efficiency of the transmission line. Hence the corona power loss can be calculated as;

$$L(corona) = 242^{(f+25)/\delta} \cdot \sqrt{\left(\frac{r}{d}\right)} \cdot (V - V^{\circ})^2 \cdot 10^{-5} \frac{kW}{Km} / Phase \qquad \ldots 2$$

Where

F denotes the frequency of transmission
δ denotes the Air density factor
r is the radius of the conductor
d the space between the transmission lines
V is the operating voltage and
V^{o} denotes the disruptive voltage.

Taking the total power loss on transmission lines to be the summation of ohmic and corona losses, then it gives the total power losss as:

$$T_{lose} = L_{ohmic} + L_{corona} \qquad \ldots 3$$

Thus

$$\tau_{lose} = I^2 R + 242^{(f+25)/\delta} \cdot \sqrt{\left(\frac{r}{d}\right)} \cdot (V - V^{\circ})^2 \cdot 10^{-5} \frac{kW}{Km} / Phase \qquad \ldots 4$$

The general form of equation (4) is given by

$$\tau_{lose} = I^2 \frac{\rho L}{A} + 242^{(f+25)/\delta} \cdot \sqrt[4]{\frac{A}{\pi_{d^2}}}) \cdot (V - V^{\circ})^2 \cdot 10^{-5} \frac{kW}{Km} / Phase \qquad \ldots 5$$

Where

ρ is the resistivity of the conductor,
L denotes the length of the conductor and
A is the cross-sectional area of the conductor.

VII. Discussions, Conclusions and Future Perspectives

The solar irradiance potential of Nigeria with 15 states and Abuja having over five hours of daily sun shine is enough to attract massive investment drive in solar renewables. The privatization experience in the Nigerian electricity sector did not go as planned as asserted by many energy experts. Most analyses have identified problems of liquidity and technical inefficiencies. However, solving the liquidity crisis needs a longer-term, holistic strategy. Proper analysis of the configuration of power in the electricity sector, a short-to-medium term strategy of devising disaggregated generation and distribution solutions is also considered inevitable.

The application of the energy trilemma concept adopted by many countries to the present power crises in the Nigeria will certainly attract investment opportunities as some of the components in the trilemma index are roadmaps to achieving UN SDGs. Although adequate data of power losses on the T & D networks are not available (to the researcher), the relative percentages of losses are calculated based on internally accepted tolerances. From the above discussions, it is found that there are various factors responsible for T & D losses that need to be eliminated. New technologies should be implemented to reduce losses i.e., Advance Metering, HVDC, and gas-insulated substations. These technologies are implemented in developed countries like China and the United States and has proved quite effective and reliable.

The future perspective required to achieve the energy trilemma concept in the Nigeria power sector should include;

1. Create attractive investment opportunities by the adoption of generation technologies that are environmental friendly, reduces carbon emission and utilises renewable energy sources.
2. Deliberate acquisition and implementation of technologies that seeks to minimise both technical and non-technical power losses to the barest minimum.
3. The political will to implement the existing acceptable policies in the power sector reforms framework.
4. Engagement of subject matter experts in the conception, implementation and evaluation of power reform policies and legislations.
5. Increase rural and off-grid or islanded microgrids to achieve higher energy penetration and rise the per capita electricity consumption of the country.
6. Localisation of power policies and program.
7. Develop local skills in the management of power sector.
8. Incorporate demand-site response designs in the power demand and supply value chains in other to match demand with instant supply.
9. Diversify the generation capacity sources of the country through partnership with donor Agencies and relevant multinational organizations.

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