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Improvement of Power Transfer with Solar System Integration on Nigeria 330 kV Transmission Grid

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Abstract

Inadequate power transfer has been one of the major issues facing Nigeria, leading to an economic crisis over the past decades. This is partly due to over-dependence on conventional and non-renewable means of power generation as the high cost of oil has led to high energy costs. This and some of the issues of low power transfer can be mitigated by delving into renewable energy generation and integration into the existing national grid. Hence, this work looked at how solar power can be utilized and integrated into the 48 bus Nigeria transmission grid for improved power transfer and reduced energy costs to consumers. The simulation was done with the NEPLAN analytical tool and MATLAB software was used for plotting the charts. From the outcome of the analysis, integration of solar system in the least locations as per the result from the optimum power flow studies resulted in improved active, reactive, and available power transfer. In the initial simulations, the real power flow varies between 6 MW to 24 MW, reactive power between 15 MVar to 33 MVar, and available transfer capability (ATC) between 12 MW and 32 MW. When the solar system was introduced in the network, the variations improved to 7 MW for the least active power which signifies 16.67% increase, and 25 MW for the most active power which signifies 4.17% increase. The reactive power increased to 16 MVar for the least bus which signifies 6.67% improvement, and 35 MVar for the highest bus which signifies 6.06% improvement. Also, the ATC increased to 12.6 MW for the least bus which indicates 5.00% improvement and 34 MW for the highest bus which indicates 6.25% improvement. The results showed that solar integration can improve power transfer, leading to lower energy cost.

1. Introduction

Nigeria's over-reliance on non-renewable and conventional power generation methods has increased power generation costs and resulted in inadequate energy output from insufficient resources and resource mismanagement [1, 2]. Furthermore, because load centers are situated far from the power sources, multilateral transactions or bulk power transfers are required. As a result of insufficient power generation, the transmission lines operate nearer and occasionally above thermal, voltage, and stability limits [3]. Operating transmission lines at their limits has resulted in poor voltage profiles, instability, large power losses, and network congestion [4]. Due to these power generation and transmission issues, the use of renewable energy has gained increasing attention in recent decades due to the sustainable and quick advancements in solar and wind power generation [5, 6].

Nigeria's present transmission system consists of thirty-two 330/132 kV substations, having 5523.8 km of 330 kV, and 6801.49 km of 132 kV, with a total installed transformer capacity of 7688 MVA. 105 number of 132/33/11 kV substations totaling 9130 MVA in installed transformer capacity. 7364 MVA of average available capacity is provided at 330/132 kV and 8448 MVA at 132/33 kV [7].

Available transfer capability (ATC) is defined by the North American Electric Reliability Council (NERC) as the total transfer capability (TTC) minus the transmission reliability margin (TRM), less than the total of the existing transmission commitments (ETCs), and less the capacity benefit margin (CBM) [8]. Where TTC denotes the maximum amount of electrical power that, under all precise pre- and post-contingency system conditions, may be reliably transported via a path in the transmission network. ETC is calculated based on a certain base case that is defined by parameters like network setups, load demands, and generator outputs [9]. TRM is defined as the transfer capability required under various uncertain system situations to guarantee the secure and consistent operation of transmission networks. CBM is a locally applied margin that load-serving organizations set aside to guarantee access to generation from other interconnected systems to satisfy requirements for generation reliability [10].

Distributed generation (DG) is a low-power production method that supplies electricity at a position closer to the customers than a central generating station by connecting to the loads of the consumers through the distribution system of a power utility [11 – 13]. Figure 1 illustrates the process of integrating solar power into the grid by inverting and increasing solar radiation power before connecting to the electricity grid.

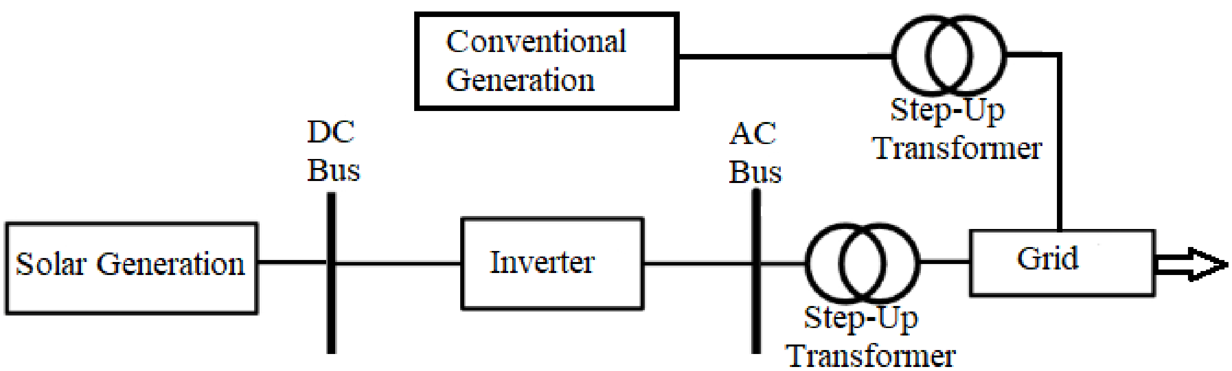

Figure 1: Block diagram of solar power system integration

However, there are certain drawbacks to the advent of this renewable energy source, chief among them being instability [14]. The stability of the system will decline with the introduction of substantial amounts of renewable energy. This can be addressed by using sodium-sulfur batteries, which primarily provide load fluctuation leveling, as well as frequency regulation [15, 16]. One of the most economically feasible forms of sustainable power is solar energy, which is the energy produced by light and which is directly turned into power by solar arrays. An inverter collector and an inverter storage device are the two components of a solar power network that collect light radiation [17]. A collector captures the sun's rays and converts some of them into various forms of power. The storage unit compensates for scenarios in which relatively little radiation may be received [18].

Much research has been going on in DG especially in renewable energy system integration to the national grid or stand-alone grid to consumers. To create multi-area representations of power systems, [19] suggested an improved aggregation method that produces estimates of the quantities required by power system planners that are more accurate. Their approach consists of dividing the initial huge power system into smaller sections and creating a smaller equivalent for each section. Available transfer capability (ATC) between each pair of network buses is the basis for partitioning. According to [20], a modified IEEE 24 bus reliability test system was used to offer a probabilistic evaluation of ATC in the presence of sporadic wind resources in the electricity network using an optimal power flow-based approach. They observed that an increase in injected wind power also increases ATC. [21] used an IEEE 30 bus test system and the reflecting slice sampling (RSS) method for risk-based ATC decisions for wind farm integration systems. They pointed out that the technique can shorten computing times, guarantee ATC correctness, and increase system transmission efficiency. For the evaluation of ATC with wind power integration, (A two-level optimization approach was proposed by [22], with the ATC evaluation being the upper-level problem and economic dispatch being the bottom level. [23] used an IEEE 24 bus test system to present a multi-stage operational strategy for improving and evaluating ATC in the presence of renewable energy sources and FACTS devices. To evaluate the available transfer capability (ATC) with wind energy integration on the IEEE test bus system, [24] presented a novel probabilistic assessment approach for this operation. For the ATC solution, they used a statistically equivalent surrogate model that was built using the standard low-rank approximation (LRA). The uncertainties associated with wind power output and load, as well as transmission equipment disruptions, are effectively handled by using LRA for the basic case and a list of specified contingencies. An ATC online evaluation approach that takes the output uncertainty of renewable energy into account was proposed by [25]. Their objective was to optimize the disparity between the revenue and operational risk associated with the integration of hybrid power into the electricity power grid. [26] described a technique for utilizing the IEEE 33 bus system to calculate the ideal placement and size of DG in a distribution system to lower losses and increase voltage stability under various loading scenarios. Their analysis's findings demonstrated that placing the DG in the best possible place can lower power losses and increase voltage stability. Proper DG size selection at the best possible location can also improve voltage stability. According to [27] dispersed generation is necessary for power systems. They mentioned that reduced transmission and distribution system resources, increased stability, and increased power efficiency are advantages of DG integration to the grid system. Similarly, [28] described the function of DG in a power distribution network's operation. They found that depending on distributed generation (DG) rather than alternating current controllers increases the dependability of DG for lowering technical losses in a distribution system. Similarly, for the benefit of utilities and customers, [29] gave a summary of definitions of distributed generation (DG) and the elements that must be taken into account when integrating DG into distribution power networks. By incorporating distributed generation into the grid and focusing on end-use applications where these DGs can beat centralized generators, they suggested decreasing the cost per kWh.

Renewable energy integration has become necessary for power transfer improvement and reduction in the cost of energy production. Several researchers have pointed out some of these renewables for integration into the grid or as a stand-alone to consumers. These studies employed various techniques for ATC assessment and augmentation. This includes ATC estimation and improvement using static var power control device (SVC), static series synchronous control device (SSSC), thyristor control device compensator (TCSC), and increasing reactive power of the line using static synchronous compensator (STATCOM) to enhance ATC. Again, most of their research focused on IEEE bus test system between the range of 10 to 40 buses. However, this work is based on solar energy integration to Nigeria's 330 kV real time 48 bus transmission grid to improve the total power transfer to consumers. It makes use of the optimum power flow deterministic method for the estimation of load flow and least power optimal locations for the installation of solar systems. These grid locations after solar installations will help improve the overall power transfer in the 48-bus network. It also compares the improvement with solar addition and with conventional generation for optimum power transfer.

2. Methodology

The following materials are used in this work;

i NEPLAN analytical tool used for the network modeling
ii MATLAB software used for the plotting of charts
iii Transmission network data from National Control Center (NCC), Osogbo

The optimum power flow (OPF) objective function as stated in [30] can be written mathematically as:

$$\text{Minimize } Y(x, \alpha, \beta, \xi_{solar}) \tag{1}$$

Subject to

$$e(x, \alpha, \beta, \xi_{solar}) = 0 \tag{2}$$

$$f(x, \alpha, \beta, \xi_{solar}) \leq 0 \tag{3}$$

Where Y stands for the objective function, e and f are equality and inequality constraint limits respectively, x denotes the state vector, α represents control variables, β represents fixed variables, ξ_{solar} represents control variables for solar power. ATC is formulated as an OPF problem in the determination of power transfer using OPF methods. This problem can be formulated by given objective function and equality and inequality constraints: max λ. The injected power in different buses is considered as the equality constraint. From the optimal load flow studies, the mathematical expression for active and reactive power injection at any bus i, as stated in [31 – 33] is given as:

$$P_i - \sum_{j=1}^{n} V_i V_j [G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})] = 0 \tag{4}$$

$$Q_i - \sum_{j=1}^{n} V_i V_j [G_{ij} \sin(\delta_{ij}) - B_{ij} \cos(\delta_{ij})] = 0 \tag{5}$$

$$P_i = P_{Gi} + P_{Wi} - P_{Di} \tag{6}$$

$$Q_i = Q_{Gi} - Q_{Di} \quad (7)$$

Where P_i and Q_i represent the injected active and reactive power at bus *i*. G_{ij} and B_{ij} represent the conductance and susceptance for the transmission line between bus *i* and bus *j* respectively.

For the inequality constraint, as stated in [34], it can be represented as:

$$\text{voltage limits:} \quad V_{imin} < V_i < V_{imax} \quad \text{and} \quad V_{jmin} < V_j < V_{jmax} \quad (8)$$

$$\text{angle limits:} \quad \delta_{imin} < \delta_i < \delta_{imax} \quad \text{and} \quad \delta_{jmin} < \delta_j < \delta_{jmax} \quad (9)$$

$$\text{active and reactive power generation at i bus: } P_{Gi\,min} < P_{Gi} < P_{Gi\,max} \text{ and } Q_{Gi\,min} < Q_{Gi} < Q_{Gi\,max} \quad (10)$$

$$\text{active and reactive power for line between i and j bus: } P_{ij\,min} < P_{ij} < P_{ij\,max} \text{ and } Q_{ij\,min} < Q_{ij} < Q_{ij\,max} \quad (11)$$

Where P_{Di} and Q_{Di} are the active and reactive power load demands at any bus *i* respectively, P_{Gi} and Q_{Gi} are the active and reactive power at any bus *i* respectively, V_j and δ_j represents voltage and angle limit at bus *j*, V_i and δ_i are the voltage and angle limit at bus *i*, $Q_{Gi\,min}$ and $Q_{Gi\,max}$ represents the limits for minimum and maximum reactive power injection at any bus *i*, $P_{Gi\,min}$ and $P_{Gi\,max}$ denotes the minimum and maximum limits of real power generation, $Q_{ij\,min}$ and $Q_{ij\,max}$ represents the limits for minimum and maximum reactive power flow from bus *i* to bus *j*, $P_{ij\,min}$ and $P_{ij\,max}$ represents the minimum and maximum active power flow from bus *i* to bus *j* respectively. The PF convergence and penalty factors (λ) respectively, impose and verify the equality and inequality constraints. As a result, the ATC between areas can be calculated. The change in real power generation and power demand at a buyer and seller bus in Equation (6) can be estimated by considering demand and generation at the corresponding buses as

$$P_{Gm} = \lambda P_{Gm}^0 \quad (12)$$

$$P_{Dn} = \lambda P_{Dn}^0 \quad (13)$$

Where *n* and *m* are the buyer and seller bus, P_{Gm} and P_{Dn} are real power generation and load demand corresponding to the bus *m* and *n* respectively. Maximum power (P_{Dn}) can be transferred between the buyer (n) and seller (m) bus by maximizing penalty or loadability factors (λ). The number of inequality and equality constraints must be satisfied to maximize λ. Hence, ATC is estimated as:

$$\text{ATC} = \lambda_{max} P_{Dn}^0 - P_{Dn}^0 \quad (14)$$

The model of probabilistic solar irradiance per beta probabilistic distribution function as stated in [33] is given as:

$$f_b(s) = \frac{s^{\alpha-1}(1-s)^{\beta-1}}{\Gamma(\alpha) \times \Gamma(\beta)} \times \Gamma(\alpha + \beta) \quad (15)$$

Where $f_b(s)$ represents the function of *s* for beta probabilistic distribution, *s* denotes the solar irradiance in w/m^2, α and β denote parameters for the function for beta distribution probability. The α and β can be determined as:

$$\alpha = \mu \times \left[\frac{(1-\mu) \times \mu}{\sigma} - 1\right] \quad (16)$$

$$\beta = (1-\mu) \times \left[\frac{(1-\mu) \times \mu}{\sigma} - 1\right] \quad (17)$$

Where σ and μ represent the standard deviation and the mean of probabilistic solar irradiance respectively. Equations (18) and (19) as stated in [35, 36] are used to calculate the output power of the solar system and mean temperature of the cell.

$$P_{PV} = \frac{P_{STC} I_S}{1000}[1 + \mu(T_C - 25)] \quad (18)$$

$$T_C = T_a + \frac{I_S}{1000}(T_{NOCT} - 20) \quad (19)$$

Where P_{STC} is the Maximum power of photovoltaic (PV) at standard test condition (STC) measured in Watts, μ is the temperature coefficient of solar, I_S is the solar irradiance in w/m^2, T_a represent the ambient temperature in ^{0}C which is 25 ^{0}C, T_C denotes PV cell temperature in ^{0}C, T_{NOCT} represent solar nominal operating temperature. The average solar radiation I_S used is 4.97 w/m^2, sun module of 249 mono modules, P_{STC} of 249 w, μ of 0045 ^{0}C^{-1}, T_{NOCT} of 45 ^{0}C.

The 48-bus network model is shown in Figure 2. The load flow is carried out using optimum power flow (OPF) employing Newton Raphson (N-R) method as explained and the results from the study which indicates five (5) least power flow were used to determine the location of installation of the solar system.

Although there are more than 48 buses in Nigeria's national grid interconnected network, this analysis is only conducted on 48 bus 330 kV transmission grid system under peak load conditions due to availability of data.

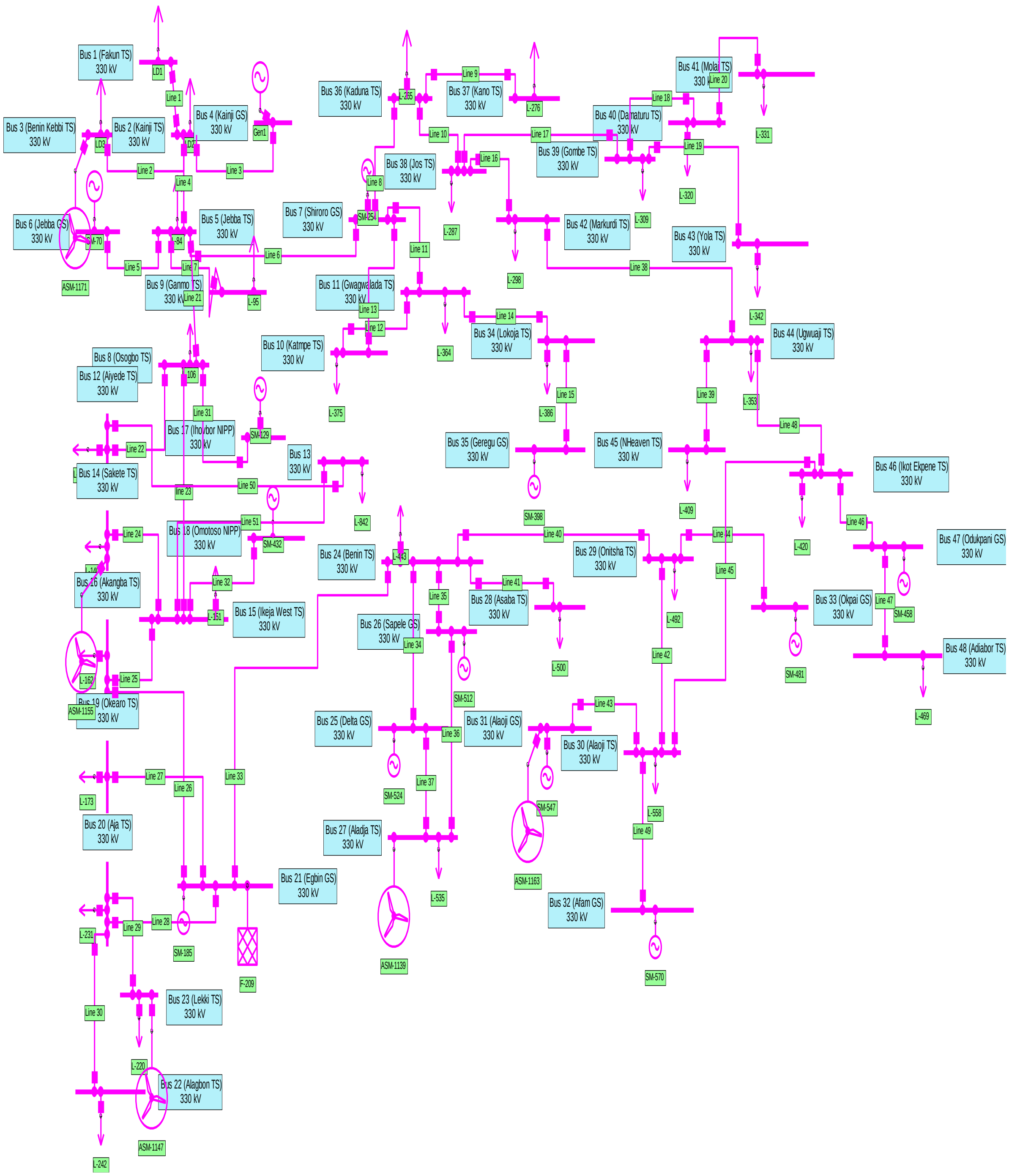

Figure 2: A network model of a 48-bus transmission grid

3. Results and Discussion

The outcome of the analysis is shown in Table 1, while the charts are represented in Figures 3 to 9.

Table 1: Power system parameters with values of the system in base case and solar system

Bus Number	Bus Name	Active Power (MW)		Reactive Power (MVar)		ATC (MW)	
		Base Case	Solar System	Base Case	Solar System	Base Case	Solar System
1	Fakun TS	21.0502	22.2943	28.6036	30.2941	23.4664	24.9018
2	Kainji TS	22.7458	24.0901	29.4918	31.2348	21.4201	22.7303
3	Birnin Kebbi TS	8.2444	8.7317	20.1101	21.2986	12.0049	12.7392
4	Kainji GS	22.8870	24.2397	28.0222	29.6784	18.6980	19.8417
5	Jebba TS	17.6545	18.6979	27.5400	29.1676	15.0977	16.0212
6	Jebba GS	7.6962	8.1511	17.8872	18.9443	28.1064	29.8256
7	Shiroro GS	11.0657	11.7197	17.0324	18.0390	18.1648	19.2759
8	Osogbo TS	16.0629	17.0122	24.4680	25.9141	22.6372	24.0219
9	Ganmo TS	23.7087	25.1100	33.5110	35.4916	15.1690	16.0969
10	Katampe TS	23.8462	25.2556	21.3715	22.6346	24.1488	25.6259
11	Gwagwalada TS	8.8147	9.3357	26.1713	27.7181	17.1720	18.2223
12	Ayede TS	23.9525	25.3681	19.0867	20.2147	25.2210	26.7637
13	Olorunsogo GS	23.7025	25.1033	29.4248	31.1639	25.9440	27.5310
14	Sakete TS	14.9177	15.7993	19.6999	20.8642	27.1570	28.8181
15	Ikeja West TS	20.7812	22.0094	24.6167	26.0716	21.0322	22.3187
16	Akangba TS	8.5219	9.0255	28.4019	30.0805	13.4850	14.3099
17	Ihovbor GS	13.7332	14.5449	32.1617	34.0626	16.4723	17.4799
18	Omotoso GS	22.9310	24.2863	33.5021	35.4821	30.5565	32.4256
19	Okearo TS	20.6309	21.8502	25.4254	26.9281	14.8959	15.8071
20	Aja TS	23.7458	25.1492	17.4170	18.4464	28.7554	30.5143
21	Egbin GS	18.0899	19.1591	17.6262	18.6679	22.8391	24.2361
22	Alagbon TS	6.5449	6.9317	19.7472	20.9143	32.2604	34.2337
23	Lekki TS	21.6908	22.9728	31.1780	33.0207	13.3689	14.1866
24	Benin TS	23.2710	24.6463	19.6839	20.8472	20.8703	22.1469
25	Delta GS	18.5181	19.6125	30.6600	32.4720	13.9549	14.8085
26	Sapele GS	19.9892	21.1706	19.4731	20.6240	31.5559	33.4861
27	Aladja TS	19.7171	20.8824	32.9136	34.8588	11.8554	12.5805
28	Asaba TS	13.1833	13.9624	21.5597	22.8339	27.7076	29.4025
29	Onitsha TS	18.0850	19.1539	18.5533	19.6498	28.5801	30.3283
30	Alaoji TS	9.0674	9.6034	19.6213	20.7809	29.6377	31.4506
31	Alaoji GS	19.0266	20.1511	26.7745	28.3569	13.4977	14.3234
32	Afam GS	6.4727	6.8553	23.9765	25.3935	19.9875	21.2101
33	Okpai GS	11.0363	11.6885	21.5925	22.8687	17.1082	18.1546
34	Lokoja TS	6.7398	7.1381	30.9843	32.8155	28.2254	29.9519
35	Geregu GS	7.6886	8.1430	26.1712	27.7180	20.6385	21.9009
36	Makurdi TS	21.2128	22.4665	25.4746	26.9802	30.5011	32.3668
37	Kano TS	18.8177	19.9298	32.6770	34.6083	15.5024	16.4507
38	Jos TS	11.7844	12.4809	20.3025	21.5024	17.1891	18.2405
39	Gombe TS	23.5731	24.9663	29.5411	31.2871	14.7552	15.6577
40	Damaturu TS	6.5214	6.9068	29.4731	31.2150	14.5603	15.4509
41	Molai TS	14.0494	14.8797	22.1567	23.4662	29.6500	31.4636
42	Yola TS	12.9846	13.7520	25.8293	27.3558	23.6903	25.1394
43	Ugwuaji TS	20.1339	21.3239	16.1868	17.1434	23.0762	24.4877
44	New Heaven TS	20.6866	21.9092	15.7574	16.6887	14.7432	15.6450
45	Ikot-Ekpene TS	9.3596	9.9128	25.1037	26.5874	29.3154	31.1086
46	Odukpani GS	14.9994	15.8859	29.9716	31.7430	24.5619	26.0643

47	Adiabor TS	14.1768	15.0147	33.0066	34.9573	18.9826	20.1437
48	Ikot Abasi GS	17.9143	18.9731	17.2461	18.2654	22.3226	23.6881

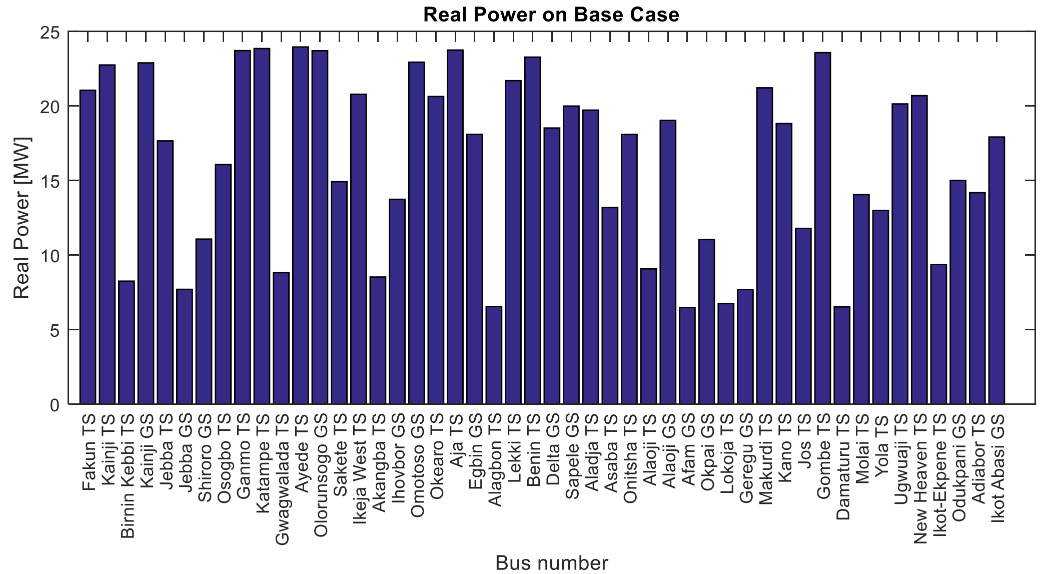

Figure 3: Real power of the network on the base case

The outcome of the analysis of conventional generation is shown in Figure 3. The real power flow varies between 6 to 24 MW. The highest active power flow on the system is recorded at 23.9 MW for Ayede TS.

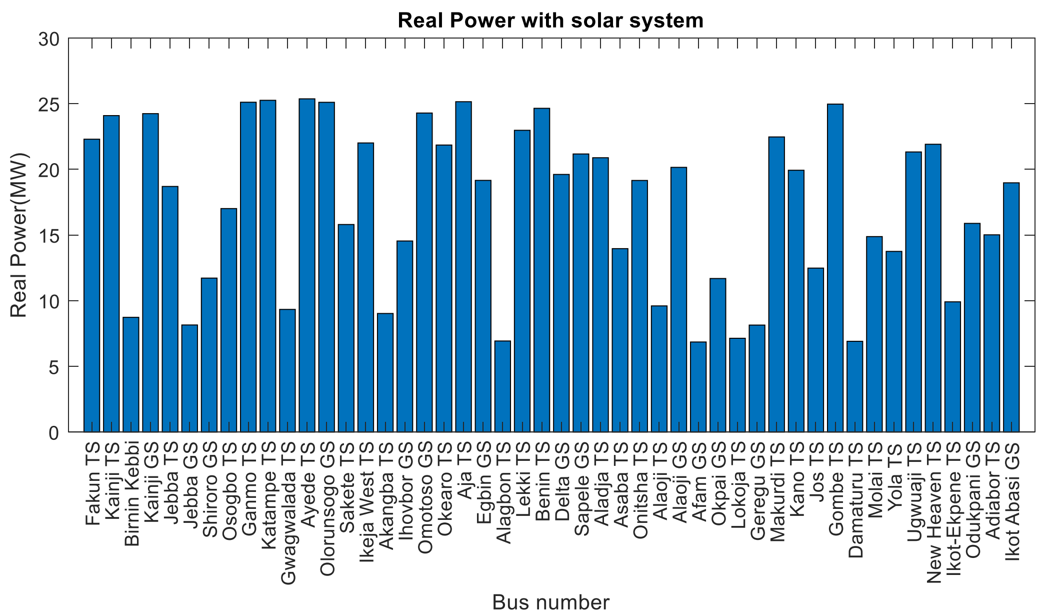

Figure 4: Real power of the system network with solar system

When solar is integrated on the buses with the least power flow after load flow studies, the real power varies between 7 to 25 MW with bus 12 increasing to 25.3 MW as the highest real power flow on the network as shown in Figure 4.

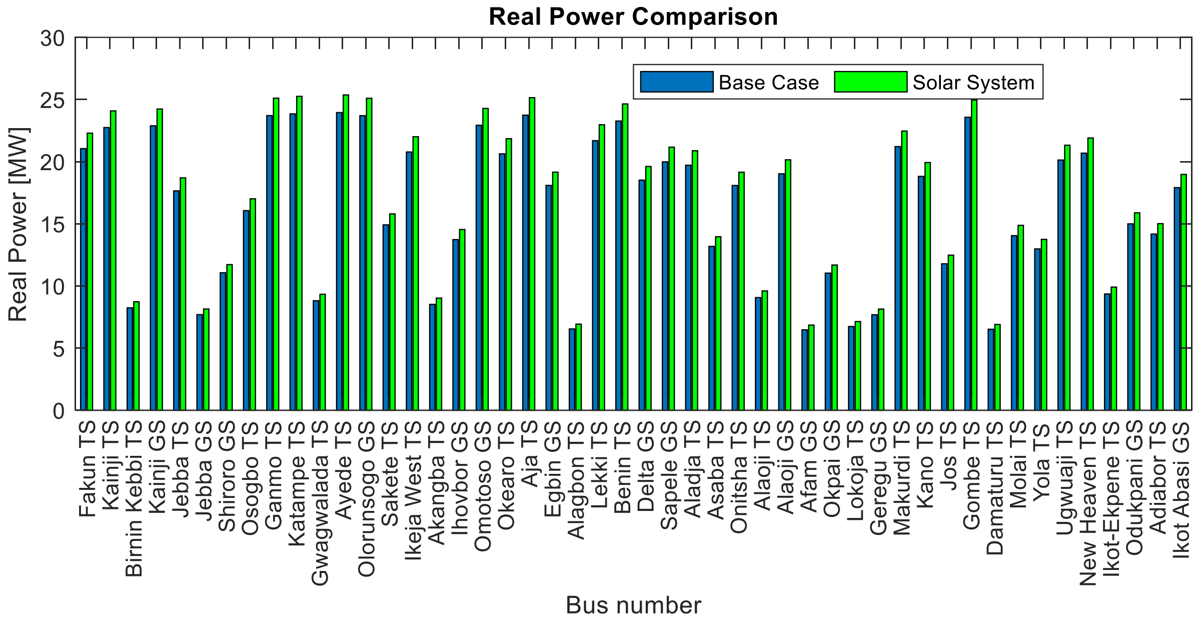

Figure 5: Real power comparison for the base case and during solar supply

Figure 5 shows the comparison between active power for the base case and solar integration to the network. It is seen that active power transfer improved greatly when the solar system was integrated in the least locations from the optimal load flow study as the least active power of 6.47 MW for Afam GS increased to 6.86 MW which signifies 6.02% increase. The most active power of 23.95 MW for Ayede TS increased to 25.37 MW which signifies 5.92% increase. This active power increase signifies improvement in the quantity of energy being transmitted to load centers which directly improve power transmission efficiency.

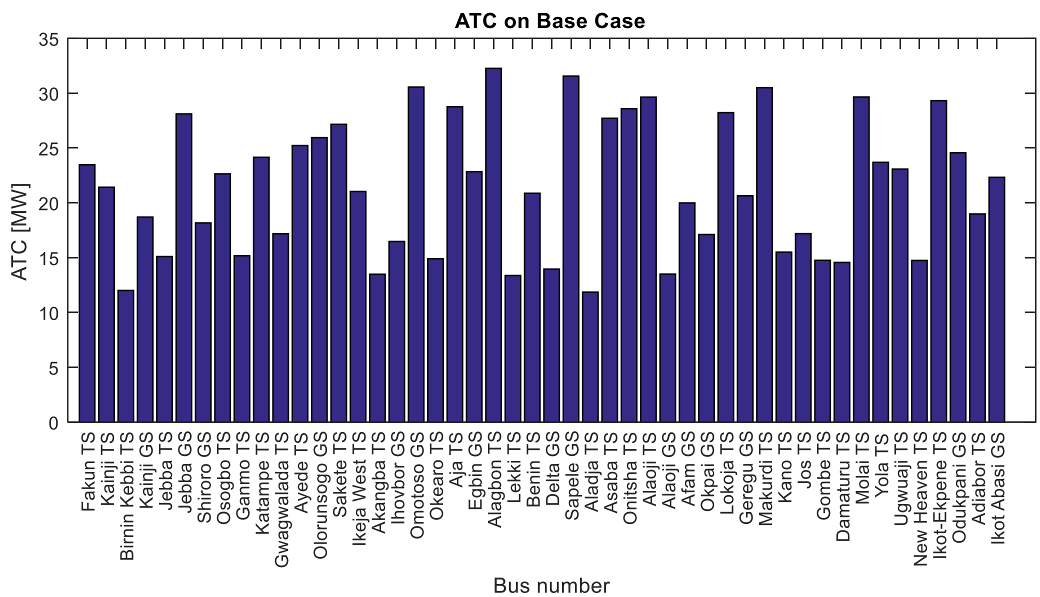

Figure 6: ATC of the power system network on the base case

From Figure 6, it is seen that the values of ATC transferred are between 12 MW and 32 MW when the system operates without any controller. It is also shown that Alagbon TS has the highest value of ATC in the network with 32.2 MW.

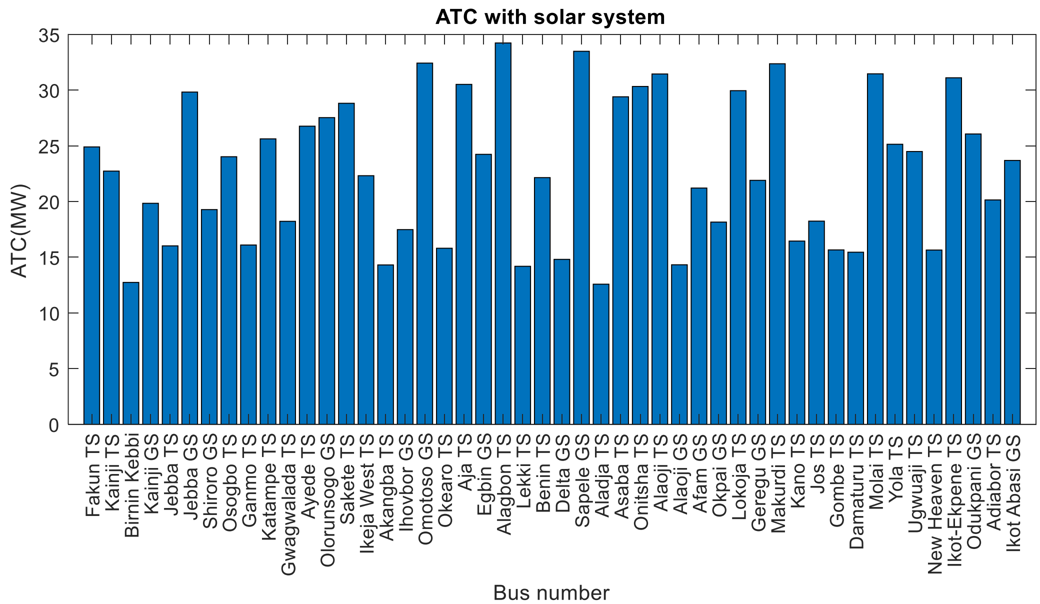

Figure 7: ATC of the power system with solar system

From Figure 7, when solar is connected to the selected buses, network ATC also improves between 12.7 to 34 MW as the value for that of Alagbon TS now stands at 34.2 MW.

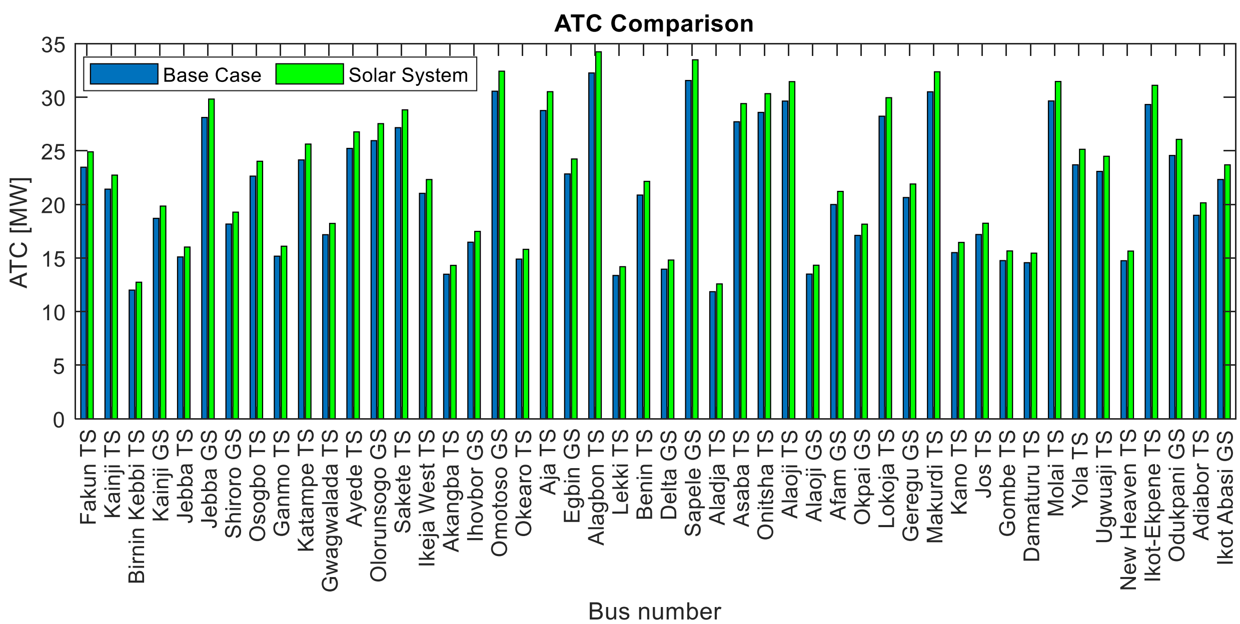

Figure 8: ATC comparison for the base case and during solar supply

Figure 8 shows the comparison between the base case and solar integration to the network for ATC computations. It is seen that ATC improved greatly when the solar system was integrated in the least locations of the network. The comparison shows that Aladja TS has the least ATC of 11.86 MW which was improved to 12.58 MW indicating 6.07% increase. Also the most ATC was recorded at bus 22 (Alagbon TS) which stood at 32.16 MW which was increased with introduction of solar to 34.23 MW indicating 6.44% increase. This shows that more power can be transferred to the consumers without risking grid stability.

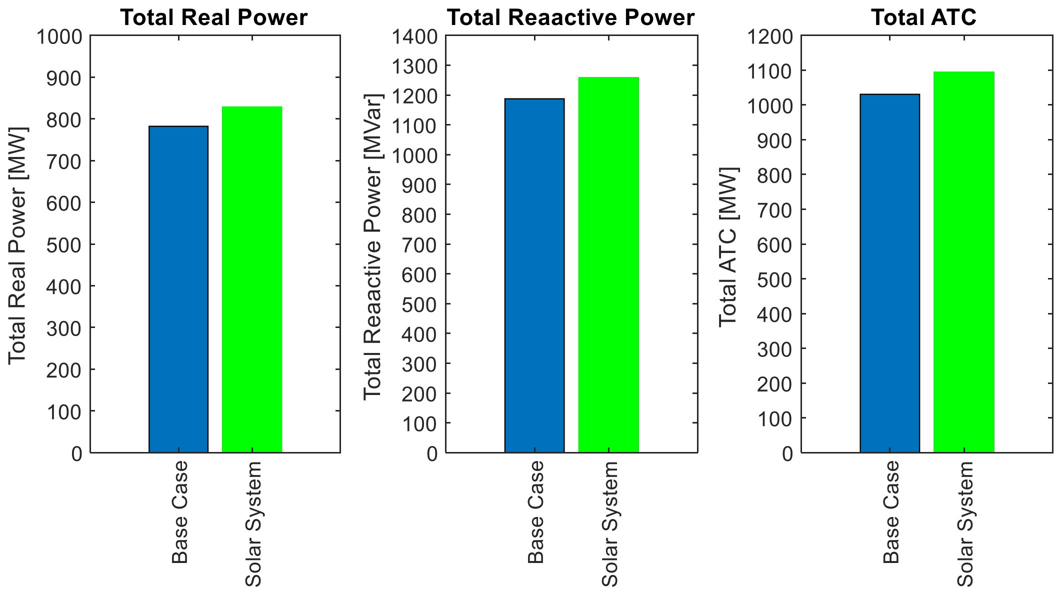

Figure 9: Total real power, reactive power, and ATC in both conditions

Table 2: Summary of the power system outcome in NEPLAN without contingency

Parameters	Base Case	Solar
Total Real power (MW)	782.0277	828.2469
Total Reactive power (MVar)	1187.2	1257.4
Total ATC (MW)	1030.5	1093.6
Maximum ATC (MW)	32.2604	34.2337

It is seen from the summary presented in Figure 9 and Table 2 that the implementation of solar systems in the least locations had an improved effect on the real, reactive power and ATC, with the values of 828.2469 MW, 1257 MVar, 1093.6 MW for total real power, total reactive power, and total ATC respectively. In comparing the results from the existing literatures, [37] showed that the total improved ATC after the implementation of the power improvement devices stood at 463 MW as against 439.97 MW total ATC without installation of any improvement device which represents 5.23% ATC improved efficiency. [38] showed that the total improved ATC after the implementation of the power improvement devices stood at 240.74 MW as against 230.34 MW total ATC without installation of any improvement device which represents 4.51% ATC improved efficiency. [39] showed that the total improved ATC after the implementation of the power improvement devices stood at 718 MW as against 652 MW total ATC without installation of any improvement device which represents 4.29% ATC improved efficiency. However, this research shows total improved ATC after the implementation of the solar system as power improvement device is 1093.6 MW while 1030.5 MW for total ATC without power improvement device which represents 6.12% ATC improved efficiency.

4. Conclusion

Power flow congestion has been the major issue surrounding the power flow of the Nigeria transmission network due to the constant increase in power demand. This led to the utilization of FACTS and solar systems for the improvement of ATC in the power system network. From the outcome of the research presented, it is observed that the integration of additional solar power sources in locations based on optimum power flow had an improved optimal effect on the real power, reactive power, and ATC of the power system network. The work showed that the real power of the network increased from 782.0277 MW to 828.2469 MW which indicates 5.91%. The total network reactive power indicates 5.91% as it increased from its base case of 1187.2 MVar to 1257.4 MVar due to solar system addition. The total ATC increased from 1030.5 MW to 1093.6 MW which signifies 6.12% increase. This suggest that power transfer is greatly improved form the additional solar system integrated on the 48 bus Nigeria power network. It is recommended that the impact of other renewable sourced power generation plants should be compared with the outcome of the solar system in Nigeria's power system network. Such renewable sources that should be considered could be the introduction of additional hydro plants, or integration of wind energy, and storage cells or combination of both. The impact of hybrid renewable energy systems on the grid or as a standalone grid which is required for sustainable operation of mini-grids in the country can equally be verified.

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