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Power Transfer Distribution Factor for Transmission Expansion Planning with Consideration on Load Growth

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Abstract: Reliable transmission expansion planning becomes highly important for effective and smooth operation of power systems. Various approaches for power system transmission expansion have been developed in the literature. The approach presented in this paper is based on the computation of network power transfer distribution factor (PTDF) using Neplan application software. The mathematical formulation of the approach based on Power Transfer Distribution Factor (PTDF) is presented. The main advantage offers by this method is that it is simple and requires no complex mathematical computation for its analysis. The Nigerian 30-bus power system network is used as a case study in this work. Based on the analysis, 12 new transmission lines are proposed for the expansion of the existing network. The results obtained show that the method is effective for transmission expansion during load growth. 30% load growth was implemented with the expanded network and the results showed no violation in bus voltages and no transmission line was overstressed.

Keywords: Transmission expansion, PTDF, Redundancy, Probability Density Function, Sensitivity, Optimization.

I. Introduction

Generally, every modern power system operates in such a way as to satisfy both the network demands and the transmission line losses, which helps in avoiding unnecessary system collapse. To achieve this function, the system is designed to contain many redundant elements. This redundancy is provided through generating capacity reserve margin, interconnection with neighbouring utilities, the addition of various transmission lines as well as alternative supply facilities. The Nigeria power system used for this study comprises eleven generating power stations, nineteen load buses and fifty-three transmission lines, which are interconnected together. These interconnections make the network to be highly efficient and economical. This paper demonstrates PTDF as a sensitivity index for power system expansion. The PTDF provides a better and more effective approach of allocating the transmission system quantities to the real power demanded, which are placed on the transmission system.

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Extensive Conventional method abounds in the literature on Transmission Expansion Planning (TEP) in electrical power systems. The main bottleneck with the conventional methods of TEP is continuous looping of values in calculation which consumes a lot of time. Various methodologies have been developed for effective TEP. The authors in [1] performed TEP using the probabilistic load flow method. The method computes PDFs for the voltage of the buses and the line flows within the network. The TEP is carried out using some criteria, which include the probability of voltage and line-flow limit violations. This is achieved using PDF associated with each random input variable. This method is faster than the conventional method of load flow solution. The conventional method needs various load values for varying load conditions. This method is cumbersome for planning due to the large number of calculations and difficulty in analysing such a large amount of results. However, the results of probabilistic load flow are based on uncertainty and therefore may be inaccurate and lead to wrong decisions.

The uncertainty can be due to forecast inaccuracy, assumption of loads within certain limits and outages. In [2]-[4] the authors worked on transmission expansion planning using an Aumann-Shapely approach based on cooperative game theory from a beneficiary pays principle. This has to do with analyzing the advantage derived by various customers connecting to the transmission lines in two categories. Category one is when the expansion project to be evaluated is considered to be in place in the system and category two is when the project is removed. The method involved the addition of a new project to be assessed to the existing network at a time. This method splits the existing group of the game into smaller groups.

Therefore, there is the possibility of achieving only an integral answer to the task, especially in a complex practical network. The authors in [5-6] proposed modified particle swarm optimization (MPSO) to solve multi-stage TEP by determining the parallel line to be included in the existing network. The modified Particle swarm optimization has the defect of taking much computing time. The best optimal solution is obtained as the particle tends to moves towards a good location within the search region.

The authors in [6] proposed novel binary particle swarm optimization (NPSO) for multi-stage TEP to decide the additional line to be connected to the existing network considering the losses and also considering the economic, technical, and how reliable is the power system. This approach successfully obtains the best solution within a short period of time compare to MPSO and also improves the deficiency observed in BPSO [6]. NPSO has a drawback of inaccurate determination of population based stochastic optimization algorithm and obtains the best solution by simulating the problem with the social behaviour of birds or bees when flocking in search of food in an area.

In [7], the author proposed an improvement to power flow in transmission networks using “static synchronous series compensator (SSSC)” to simultaneously control line impedance, voltage magnitude and phase angle and to improve the power flow. SSSC also improve the voltage stability and reduce power oscillation damping in a few seconds without affecting the balance or the stability of the system. The device comprises a coupling transformer, a magnetic interface, voltage source converters (VSC) and a dc capacitor. The advantage of this method is that it controls both the active and reactive line power flow to control the voltage and the phase angle. The drawback lies with the formulation and inversion of Jacobian matrix and large storage requirement that is involved with Newton-Ralphson iterative method used in Neplan software in this paper.

In [8], the authors proposed a probabilistic load forecast and algorithm for long term transmission expansion planning of the Nigerian transmission network. A developed approach for the system consists of an artificial neural network and Monte Carlo simulations. The proposed approach considered predominant driving factors of the location as population and GDP growth of the Nigerian system. The responses of the system time-step identified possible reinforcement requirements as well as guides for the existing Nigerian power grid for its long-term development. This approach takes into consideration how the probabilistic growing load could be effectively accommodated. The results obtained from the analysis show a better improvement over deterministic-based. The drawback of this method is uncertainty in forecast inaccuracy and can lead to wrong decisions. In [9], the authors carried out TEP using PTDFI implemented by Neplan software. This method considered a violation of power flow on the transmission lines and violation of bus voltage to propose additional transmission lines. Violation of line flow and violation of bus voltage indicate weak transmission lines and weak buses respectfully. This method showed that the transmission network expansion has improved the performance of the transmission network with a minimum loss of 3.5% recorded. This loss can be further reduced for optimum power flow. The authors in [10] presented (AC-TEP) model for reactive power planning (RPP). The method explored the use of Monte Carlo simulation to determine the expected energy not supplied (EENS) for the reliability enhancement. particle swarm optimization (PSO) technique is employed for solving the problem which is formulated as a nonlinear mixed-integer optimization problem. The results obtained using Garver and RTS systems as test cases showed that the proposed scheme is effective for reducing the total cost of investment as well as increasing the system's social welfare. This approach is used to achieve cost minimization. In [11], a novel deterministic-based approach for the reinforcement of the static transmission network in a restructured power markets with high levels of uncertainties is proposed. The problem is formulated as an optimization problem and solved using analyses based on the N−1 criterion. However, this method cannot be used for dynamic transmission network.

II. Materials and Methods

A. Modelling Power Transfer Distribution Factor (PTDF)

The power flows on the individual transmission lines of the system are modelled. This enables power system engineers to check whether any line is overloaded or not [7].

The active and non-active power flow from bus k is determined from equations (1) and (2) respectively.

$$P_{ik} = -|V_i|^2 |Y_{ik}| \cos\theta_{ik} + |V_i||V_k||y_{ik}| \cos(\theta_{ik} - S_i + S_k) \tag{1}$$

$$Q_{ik} = |V_i|^2 |Y_{ik}| \sin\theta_{ik} - |V_i||V_k||Y_{ik}| \sin(\theta_{ik} - S_i + S_k) - |V_i|^2 |y_{ik}^0| \tag{2}$$

A change in the generation of power that is injected into the system at one bus (i.e. generator) and drawn at another bus by a load. The coefficient of the linear relationship between the amounts of a change in a generation to the change in power flow on the transmission lines l-m is represented by PTDF.

$$\boldsymbol{PTDF}_{lm,ki} = \frac{\Delta \boldsymbol{P}_{lm}}{\boldsymbol{P}_{ki}} \tag{3}$$

where k is Generator bus (source), i is Load bus (sink), l-m is transmission line (from l to m), ΔP_{lm} is change in power flow on transmission line lm and P_{ki} is power transacted.

Suppose there exists only one transaction P_t from bus k (source) to bus i (sink). Change in power in the buses will be given as:

$$\begin{aligned} \Delta P_k &= +P_k \\ \Delta P_i &= -P_i \\ \Delta Q_k &= 0 \\ \Delta Q_i &= 0 \end{aligned} \tag{4}$$

where (k=1,…..n ,k ≠ i, j).

$$\Delta P_{lm} = \left[\frac{\partial P_{lm}}{\partial \delta_2}, \ldots\ldots, \frac{\partial P_{lm}}{\partial \delta_n} \frac{\partial P_{lm}}{\partial V_{g+1}}, \ldots\ldots, \frac{\partial P_{lm}}{\partial V_n} \right] [J^{-1}] \begin{bmatrix} 0 \\ : \\ +P_t \\ 0 \\ : \\ -P_t \\ 0 \end{bmatrix} = d_t P_t \quad (5)$$

where d_t is the (PTDF), δ is the load angle, V is the bus voltage magnitude and J is the Jacobian matrix.

The effect of multiple transactions in the flow of line $l-m$ can be obtained by superposition as we have in equation 5 [9], [13].

B. Modelling the Load Growth

The effect of load addition on the system operation should be reflected in the expansion plan. This is to ensure that the addition of a new load does not completely change the operation and hence production cost. On this basis, adequate construction and improvement can then be carried out on the system. Assume that the power P_i increases at the same fractional rate each year, then the change of P_i overtime is

$$\frac{dP_1}{dt} = P_i t \quad (6)$$

Integrating equation (6) from t = 0 to t = t_1

$$\int_{P_0}^{P} \frac{dP_i}{P_i} = \int_{t=0}^{t=t_1} i dt;\ In\left(\frac{P}{P_0}\right) = it_1,$$
$$P = P_0 e^{it_1}\ joules/yr \quad (7)$$

Where t is in years, and i is in per unit/years, P is in Joules/years.

For a constant growth rate, the variation of energy consumption can be obtained. The total energy consumed during a given period of time can be obtained by integration.

$$E_0 = \int_{-\infty}^{t_1} P d_t = \int_{-\infty}^{t_1} P_0 e^{it} dt \quad (8)$$

$$E_0 = \frac{P_0}{i} e^{it_1} \quad (9)$$

Now, let E_1 be the total energy consumed between t = t_1 and t = t_2

$$E_1 = \int_{t_1}^{t_2} P_0 e^{it} dt = \left[\frac{P_0}{i} e^{it}\right]_{t_1}^{t_2} = \frac{P_0}{i}\left[e^{it_2} - e^{it_1}\right] \quad (10)$$

$$E_1 = \frac{P_0 e^{it_1}}{i}\left[e^{i(t_2-t_1)}\right] = E_0\left[e^{i(t_2-t_1)} - 1\right] joules \quad (11)$$

Table 1: Bus No/Bus Name for the 30-bus, 330 kV Nigerian Transmission Network

Bus No	Bus Name	Bus No	Bus Name	Bus No	Bus Name
1	Egbin	11	Akangba 1	21	Birnin Kebbi
2	Delta	12	Ikeja west 1	22	Gombe
3	Afam	13	Ajaokuta	23	Jebba TS
4	Jebba GS	14	Aladja	24	Jos
5	Kanji GS	15	Benin	25	Kaduna
6	Shiroro	16	Aiyede	26	Kano
7	Sapele	17	Osogbo	27	Calabar
8	Okapi	18	Alaoji	28	Katampe
9	AES	19	New haven	29	Omotoso
10	Aja	20	Onitsha	30	Papalanto

C. The Sample Network

The sample network plan is as displayed in Figure 1

III. Results and Discussion

The sampled network (Figure 1) consists of fifty-three transmission lines, thirty buses as shown in Table 1 (eleven generator buses and nineteen load buses) respectively. The power flow results for the network shows that six of the buses (Calabar, Gombe, Jos, Kano, New haven and Onitsha) had voltage magnitudes less than the statutory limit of 100 ±5 % of nominal voltage. Their voltage magnitudes are 0.93, 0.66, 0.81, 0.81, 0.90 and 0.94 in per unit respectively as shown in Figure 2. The results for line flow and losses presented five overstressed transmission lines as their line flows exceed the line flow limit of 448 MVA. These overstressed transmission lines are

Ikeja-Omotosho, Alaoji-Onitsha, Egbin-Ikeja, Alaoji-Calabar and Okpai-Calabar. Also, the total active power loss within the network was found to be 219.08MW.

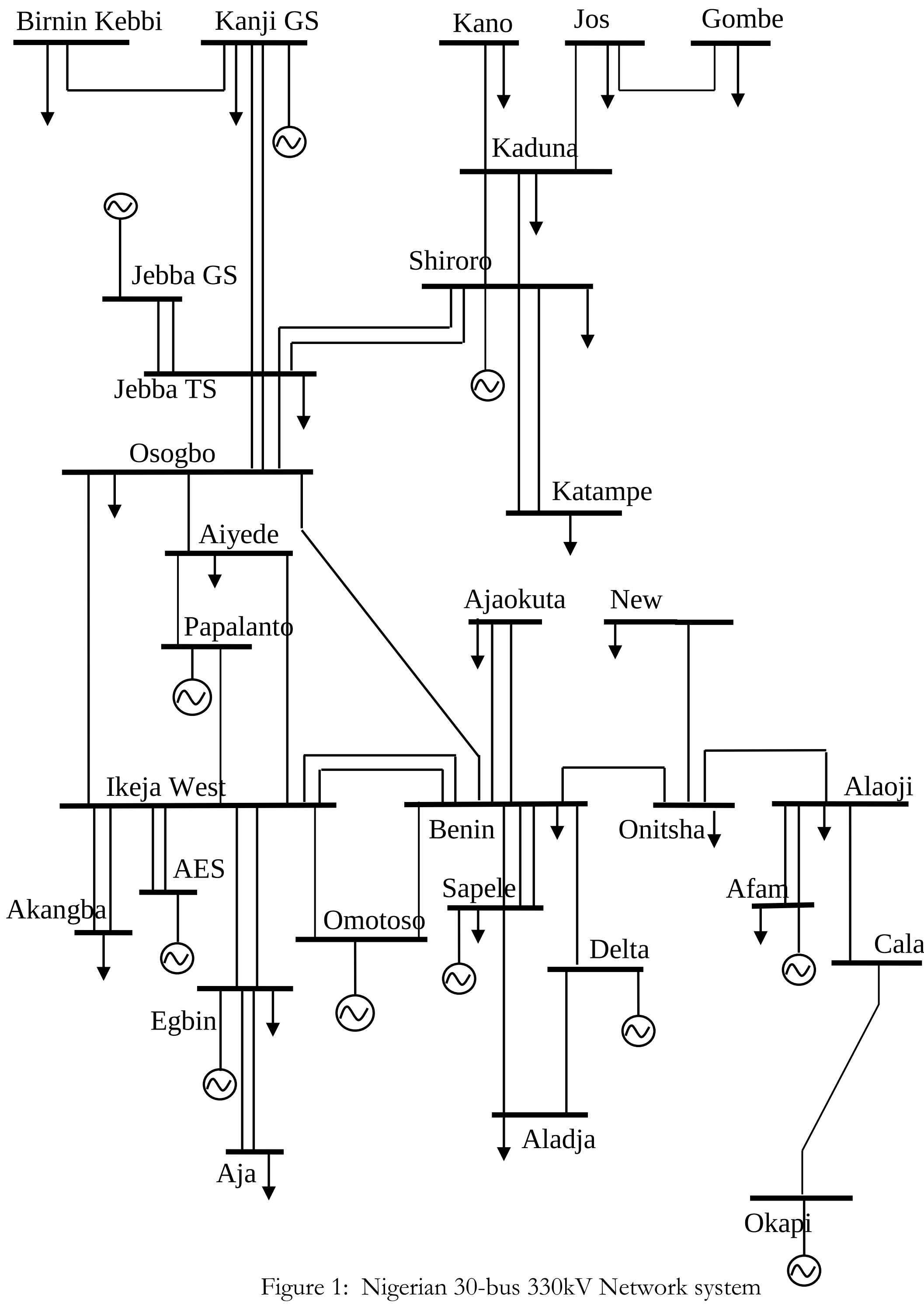

Figure 1: Nigerian 30-bus 330kV Network system
(Source: National Control Centre, Power Holding Company of Nigeria, 2015)

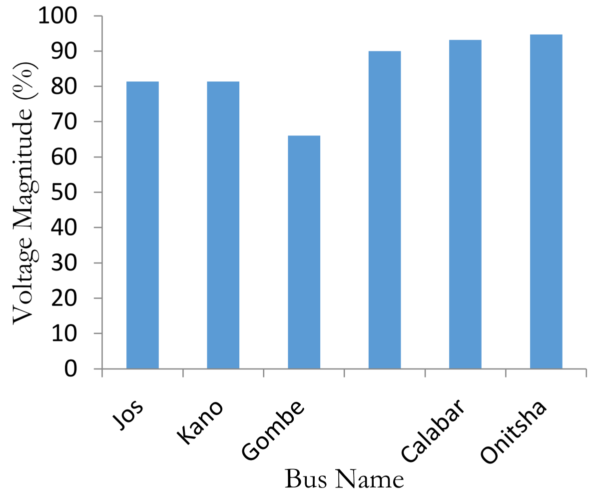

Figure 2: Voltage magnitudes of six buses that violated the statutory limit.

Power Transmission Distribution Factor PTDF was applied to the network. The lines where the PTDFI are greater than or equal to unity are considered to be overstressed. With the application of PTDFI, twelve transmission lines are overstressed as shown in Table 2 as the proposed transmission lines. The proposed twelve transmission lines were incorporated to the sample network and the power flow was performed on the new network. The active power loss decreased from 219.08 MW to 109.67 MW and all bus voltages fell within the statutory limits and no transmission line was overstressed.

To show the effectiveness of the expanded network, the expanded network was simulated considering various percentage load growth. Table 3 shows the power flow results for thirty per cent load growth implementation with the expanded network. The results obtained from the simulations showed no violation in the magnitude of the voltage at various buses and none of the transmission lines was overstressed until the load growth exceeds thirty per cent. The new power loss at thirty per cent load growth is 128.95 MW. This indicates that the proposed transmission expansion would be able to serve effectively the existing network plus thirty per cent growth in load

With this approach, the percentage power loss is 2.5% while the percentage power loss with the conventional power flow approach is 3.5%. The voltage profile with this proposed method is more even than the PDF approach. Likewise, the approach in this paper could be used for long term load forecast. In this work, the proposed expansion would be able to handle 30% load growth while the conventional load flow and PDF approaches are used to get quality supply for the existing network.

Table 2: The Transmission Lines with PTDF ≥ 1

Load Bus	LINE	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9	Bus 29	Bus 30
Jos	L 24-25	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Kano	L 25-26	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07
Gombe	L 24-25	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33
New Haven	L 22-24	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16
Calabar	L 15-20	1.02	0.09	1.02	1.02	1.02	1.02	0.33	1.02	1.02	1.02
Onitsha	L 19-20	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
Ikeja	L 12-29	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31
Alaoji	L 18-20	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21
Onitsha	L 20-18	1.16	1.25	1.23	1.03	1.03	1.02	1.26	1.13	1.16	1.49
Okpai	L 8-27	1.03	1.02	1.01	1.03	1.04	1.05	1.07	1.07	1.02	1.07
Omotoso	L 12-29	1.16	1.25	1.22	1.03	1.01	1.02	1.26	1.13	1.16	1.51
Alaoji	L 18-27	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.14	1.09	1.09

Table 3: Power Flow for Nigerian 30-bus Network with Twelve Proposed Lines at 30% Load Growth.

BUS NAME	Voltag%	Angle	Load(MW)	Load (MVar)	Gen. MW	Gen.MVar
AES	105.00	1.50	0.00	0.00	750	149.33
Afam	105.00	5.80	52.50	39.40	431.00	981.98
Aiyede	98.99	-3.50	358.54	268.84	0.00	0.00
Aja 10	104.34	-0.40	356.72	267.54	0.00	0.00
Ajaokuta	104.10	0.50	17.94	13.39	0.00	0.00
Akangba	101.01	-1.20	448.11	336.05	0.00	0.00
Aladja	104.36	4.20	125.45	94.12	0.00	0.00
Alaoji	101.48	5.30	555.10	416.26	0.00	0.00
Benin	103.39	0.80	498.29	373.75	0.00	0.00
BirninKebi	95.94	-8.70	148.85	111.67	0.00	0.00
Calabar	100.00	6.60	143.00	115.70	0.00	0.00
Delta	105.00	5.80	0.00	0.00	670.00	42.55
Egbin	105.00	0.00	68.90	51.70	695.33	794.24
Gombe	100.00	-36.4	169.78	127.27	0.00	0.00
Ikeja west	101.99	-0.60	823.16	617.37	0.00	0.00
Jebba GS	105.00	-4.00	0.00	0.00	495.00	155.58
Jebba TS	104.80	-4.30	14.69	10.66	0.00	0.00
Jos	100.00	-32.2	91.39	68.59	0.00	0.00
Kaduna	101.29	-27.8	250.90	188.11	0.00	0.00
Kanji GS	105.00	-1.30	7.00	5.20	624.70	36.18
Kano	100.00	-33.4	286.78	185.77	0.00	0.00
Katampe	101.82	-24.4	377.13	188.50	0.00	0.00
New haven	100.00	-1.60	231.27	173.42	0.00	0.00
Okapi	105.00	10.00	0.00	0.00	750.00	465.96
Omotoso	105.00	1.30	0.00	0.00	410.00	308.28
Onitsha	100.00	0.30	239.98	179.92	0.00	0.00
Osogbo	101.89	-4.30	261.56	196.17	0.00	0.00
Papalanto	103.12	0.40	0.00	0.00	342.10	156.00
Sapele	105.00	1.80	20.60	15.40	190.30	357.06
Shiroro	105.00	-21.7	70.30	36.10	388.90	604.29

IV. Conclusion

In this paper, the transmission expansion planning considering load growth for the Nigerian 30-bus grid system has been presented. The Nigerian transmission network is characterized by high losses and a poor voltage profile. Twelve transmission lines are proposed using PTDF and overloaded lines approach utilizing Neplan application software. The addition of proposed lines in parallel with the existing lines caused a reduction in the total impedance of the network. The reduction in the impedance led to a reduction of line losses and improved voltage profile. With the reduction of losses and voltage stability improvement, this network is appropriate to supply quality power as load increases by 30%. This indicates that this approach is effective for transmission expansion planning when taking into consideration the influence of load growth within the network.

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