Assessment of Transmission Lines Operational Resilience Using Power Transfer Distribution Factor Index for Proactive System Operational Planning

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***Abstract*— The Electricity Reform Act of 2005 in Nigeria was instituted due to the continuous rapid increase in electrical power demand from over 200 million Nigerian. The reform encouraged private sector participation in the generation of more electrical energy. Unfortunately, expansion of transmission network (TN) was given less attention by the Government. Hence, the transmission network was over loaded, and in critical condition that cannot accommodate all the power generated simultaneously. This paper estimates the resilience of transmission network of Nigeria 30-bus grid system under this condition using Power Transfer Distribution Factor Index (PTDFI). The Newton-Ralphson iterative power flow technique was used to determine the steady state condition of the TN. As the generation and load were varied, the line flows on each transmission line keep changing. The variation in power flow on each transmission line is sensitive to the strength of the line. The simulation results showed that the most critical line is from Jos to Kaduna with PTDFI of 1.3271 and the most strengthened line is from Ikeja West to Benin with PTDFI of 0.2085. From this result, it is discovered that Jos to Kaduna transmission line needs urgent enhancement, closely followed by Gombe to Jos. The PTDFI is a good approach to fast track transmission network expansion and resilience enhancement for power system operation.**

Keywords*— *Electricity reform act, Transmission network expansion, Transmission line resilience enhancement, Power Transfer Distribution Factor Index

I. INTRODUCTION

Power system consists of generation, transmission and distribution. Generated power is carried out at generating station while consumers are at the distribution end of the power system chain. If the transmission network is not capable to accommodate all the power generated, it will cause stranded generation and results to load shedding. On the other hand, if the transmission lines are under-utilized, it will leads to loss of resources. Therefore, for optimum power system operation, transmission network is designed to accommodate power generated and transfer quality power to consumers at minimum loss [1- 2].

In 2005,the Nigeria power system was privatized. The aim was to cope with rising in load of consumers and to get reliable power supply. This served as an opportunity for the private investors to be involved in electricity generation and distribution while transmission is still regulated. This has led to insufficient capacity of the transmission lines to accommodate the available generated power to the consumers. Hence, it led to overstressing the transmission lines, poor voltage gradient and high losses [3].

To operate any power system efficiently, and to carry out possible future expansion on the transmission network of the system, the strength of each transmission line of the network must be ascertained. The steps involved for the determination of the strength of transmission line commence with power flow analysis to obtain steady state solution. The next is to consider variation in load and variation in generation to match. While the loads and generations are varied, the power flow as well as the line flow must be maintained at steady state to obtain quality power supply. This implies that none of the transmission lines or cables is overstressed and voltage magnitudes and voltage angles are not violated. If the thermal loading limit of transmission line is exceeded, it will lead to increase in the conductor temperature [4]. This will increase the sag of the transmission lines between the towers and if it is not checked may results in irreversible stretching. Therefore, such lines are described as critical and overstressed. Variation in generation or load at a bus or switching on/off of a line or a transformer will reach other places in the network through transmission lines thereby changing the power flow on all transmission lines [5]. The consequences of the changes in line flow may be experienced in various degrees on different transmission lines, depending on electrical characteristics of the lines and the interconnection [6]. The response of each transmission line to change in loading condition depends on the fragility (strength or weakness) of such line. This fragility of the transmission line is determined in this paper using PTDFI. The PTDFI measures the strength or the weakness of the transmission line and can be employed to determine the strength of the transmission network.

Many researchers have proposed different model and tools to obtain the strength of the transmission line which include linear and non-linear mixed integer optimization programming techniques.

Determination of the strength of transmission line is a complex task, which often involves the use of sophisticated mathematical modeling and optimization techniques [4]. The solution to the sophisticated mathematical modeling is usually broken down into steps.

In a realistic power system network, the committed units of power plants are at different location from load centre. Under steady state condition, the generation capacity is equal to the load demand plus loses [7]. Thus, there are many ways of scheduling generation to feed the loads.

Authors in [8] worked on Nigerian transmission network using long term load forecast algorithm. This approach broke down the system to artificial neural network and Monte Carlo simulations and takes into consideration how the probabilistic growing load could be effectively accommodated.

In [9], the authors carried out study on power transmission network for the Nigerian South East Electric Power system using Power World Simulator software. He analysed transmission network using contingency analysis of "N-I" criteria to evaluate potential transmission system and help in selecting the best plan for overall system security.

Recently, a comprehensive and novel methodology based on power transfer distribution factor is presented by authors in [10]. The work considered a linearized power system network and avoids the use of voltage angle at the network nodes. Consequently, both the computational and time complexities are reduced significantly as the number of constraints are reduced compared to the optimization-based approach..

II. METHODOLOGY

If the system operator is desired to increase generation into the infinite bus-bar, the valve must be opened more to increase steam into the turbine couple to the generator thereby increasing the shaft mechanical power. As a consequence, the electrical output power increases and so the voltage angle increases. The PTDFI is described as the relationship that exists between the amount of power generated and the power flow on a line as the load also varied. It is described as sensitivity approach since it computes the amount of a change in generation and load to change in power flow on the line. Any transmission line that has value of PTDFI greater than one or equal to one is considered to be weak and vice versa.
Consider real power 'P' generated at bus 'j' and taken out at load buses 'k', as given in (1).

$$P_G = V_j \sum_{k=1}^{k=n} Y_{jk} V_j \cos\left(\theta_{jk} + \delta_j - \delta_k\right) \quad (1)$$

The power demanded is given in (2).

$$P_D = V_k \sum_{k=1}^{k=n} Y_{kj} V_k \cos\left(\theta_{kj} + \delta_k - \delta_j\right) \quad (2)$$

Where, V is voltage magnitude, Y is the admittance, δ is the voltage angle and θ is the load angle. For a steady state condition, total power generated is equal to total power demanded plus total losses on the transmission lines as given in (3).

$$\sum_{j=1}^{n_g} P_G = \sum_{k=1}^{n_d} P_D + P_L \quad (3)$$

Where n_d is the load buses and n_g is the generating plant. Power loss (P_L) on the transmission line is presented by the author in [11] as given in (4).

$$P_L = \sum_{i=1}^{n} \sum_{j=1}^{n} \left[\frac{R_{ij} \cos\left(\delta_i - \delta_j\right)}{\left|V_i\right|\left|V_j\right|} \right] \left(P_i P_j + Q_i Q_j\right) \quad (4)$$

where R is the resistance of the line, Q is the reactive power, V is the voltage and δ is the voltage angle. To determine the strength of each transmission line, generation and load were varied to maintain steady state operation. The power loss was neglected since sensitivity index was considered to study the change in power flow on each line. Also, the variation in generation is limited by the inequality constraint in (5).

$$P_{i(\min)} \le P_i \le P_{i(\max)} \quad i = 1,2,3........n \quad (5)$$

where Pi (min) and P*i* (max) is the minimum and maximum generating limit for plant *i*. When losses are negligible in (3) and using the inequality in (5), we have (6).

$$\left| \frac{\sum_{k=1}^{n_g} P_k}{\sum_{i=1}^{n_d} P_i} \right| \le 1 \quad (6)$$

Hence, the measure of power flow on any transmission line to varying generation with varying load is given by (6).
Equation (6) gives the power flow index on the transmission lines. Hence, the transmission line with the largest PTDFI is the most critical line within the network.

III. STRUCTURE OF THE NIGERIAN 330 KV TRANSMISSION SYSTEMS

Figure 1 (sample network) shows the structure of the Nigerian 30-bus 330 kV transmission network. It contains the

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name of the each bus, eleven generating stations, nineteen load buses and fifty-three transmission lines.

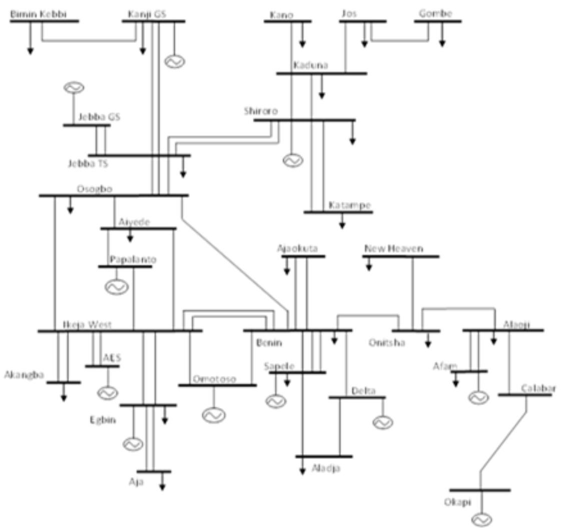

Fig. 1. Nigeria Power Network (Source:National Control Centre,Power Holding Company of Nigeria,2015)

IV. Results and Discussion

The 330 kV, 30-bus Nigerian power system was simulated using Newton-Ralphson power flow method. Table I shows the power flow and losses on the transmission lines for initial power flow.

TABLE I. The Initial Power Flow and Losses on the Transmission Lines

BUS	P (MW)	Q (Mvar)	S (MVA)	P LOSS (MW)	Q LOSS (Mvar)
AES 9	375.00	82.09	383.88	8.20	5.89
Afam 3	189.25	403.08	445.29	1.82	8.20
Aiyede 16	14.63	-52.49	54.49	0.09	-26.62
Aiyede 16	-146.91	-55.56	157.07	1.05	-15.34
Aiyede 16	-143.52	-98.75	174.21	1.12	3.47
Aja 10	-137.20	-102.90	171.50	0.16	-2.06
Ajaokuta	-6.90	-5.15	8.61	0.02	-41.17
Akangba	-172.35	-129.25	215.43	0.31	-1.19
Aladja 14	-353.63	-9.02	353.75	1.37	3.73
Aladja 14	257.13	-63.38	264.83	1.59	-1.77
Alaoji 18	512.11	138.02	530.38	16.50	95.66
Alaoji 18	-564.25	331.54	654.44	30.17	189.81
Alaoji 18	-187.43	-394.88	437.11	1.82	8.20
Benin 15	150.73	-21.16	152.20	2.34	-40.38
Benin 15	6.92	-36.02	36.68	0.02	-41.17
Benin 15	90.94	-24.47	94.17	0.76	-46.64
Benin 15	-127.10	232.74	265.19	3.90	2.76
Benin 15	72.38	-100.18	123.59	0.33	-1.06
Benin 15	-311.11	-4.82	311.14	3.89	5.84
Benin 15	-141.23	-92.14	168.63	0.51	-6.87
Benin 15	-141.23	-92.14	168.63	0.51	-6.87
Benin 15	6.92	-36.02	36.68	0.02	-41.17
BininKebi	-114.50	-85.90	143.14	2.08	-47.12
Calabar	594.42	-141.74	611.08	30.17	189.81
Calabar	-704.42	52.74	706.39	45.58	302.56
Delta 2	355.00	12.75	355.23	1.37	3.73
Delta 2	315.00	10.67	315.18	3.89	5.84
Egbin 1	137.36	100.84	170.40	0.16	-2.06
Egbin 1	-402.22	246.11	471.54	4.71	23.42
Gombe 22	-130.60	-97.90	163.22	6.56	16.95
Ikeja west	406.93	-222.68	463.87	4.71	23.42
Ikeja west	172.66	128.06	214.97	0.31	-1.19
Ikeja west	-148.39	-19.22	149.63	2.34	-40.38
Ikeja west	-14.53	25.88	29.68	0.09	-26.62
Ikeja west	-76.12	-23.99	79.81	0.55	-47.63
Ikeja west	-475.15	-47.39	477.51	6.90	48.39
Ikeja west	-196.20	-49.33	202.31	1.26	4.46
Ikeja west	-366.80	-76.20	374.63	8.20	5.89
Jebba GS	247.50	27.25	249.00	0.11	0.05
Jebba TS	112.67	21.36	114.68	0.78	-27.08
Jebba TS	112.67	21.36	114.68	0.78	-27.08
Jebba TS	-247.39	-27.20	248.88	0.11	0.05
Jebba TS	-248.72	27.19	250.20	1.84	-3.79
Jebba TS	321.46	-36.13	323.48	9.02	14.97
Jos 24	137.16	114.85	178.90	6.56	16.95
Jos 24	-207.46	-167.55	266.68	8.16	29.31
Kaduna	229.44	173.89	287.89	8.84	30.99
Kaduna	-319.03	-257.73	410.13	6.75	31.35
Kanji GS	116.58	38.78	122.87	2.08	-47.12
Kanji GS	250.56	-30.98	252.47	1.84	-3.79
Kano 26	-220.6	-142.90	262.84	8.84	30.99
Katampe	-145.05	-72.50	162.16	0.90	-13.61
Newhaven	-177.90	-133.4	222.36	2.11	0.54
Okapi	750.00	249.83	790.51	45.58	302.56
Omotoso	482.05	95.78	491.47	6.90	48.39
Omotoso	-72.05	99.13	122.54	0.33	-1.06
Onitsha 2	131.00	-229.98	264.68	3.90	2.76
Onitsha	-495.61	-42.36	497.42	16.5	95.66
Onitsha	180.01	133.94	224.38	2.11	0.54
Osogbo	76.68	-23.63	80.23	0.55	-47.63
Osogbo	-90.18	-22.17	92.87	0.76	-46.64
Osogbo	147.96	40.22	153.33	1.05	-15.34
Osogbo	-111.89	-48.44	121.92	0.78	-27.08
Osogbo	-111.89	-48.44	121.92	0.78	-27.08
Papalanto	197.47	53.79	204.66	1.26	4.46
Papalanto	144.63	102.21	177.11	1.12	3.47
Sapele	-255.54	61.61	262.87	1.59	-1.77
Sapele	141.75	85.27	165.42	0.51	-6.87
Sapele	141.75	85.27	165.42	0.51	-6.87
Shiroro	-312.43	51.10	316.58	9.02	14.97
Shiroro	145.95	58.89	157.38	0.9	-13.61

Table II shows the ranking of the transmission lines according to their sensitivity using PTDFI for varying load and generation. It shows that the most critical line is Jos to Kaduna with PTDFI of 1.3271 and the least fragile line is Ikeja West to Benin with PTDFI of 0.2085.

TABLE II. The Ranking of Transmission Lines

From Bus	To Bus	PTDF	Ranking	From Bus	To Bus	PTDF	Ranking
Jos	Kaduna	1.3271	1	Ikeja West	Omotoso	0.6701	18
Gombe	Jos	1.1611	2	Aiyede	Papalanto	0.6429	19
Kaduna	Kano	1.0728	3	Benin	Oshogbo	0.5568	20
Kanji GS	BirninKebbi	1.0305	4	Kanji GS	Jebba TS	0.5152	21
Benin	Onitsha	1.0195	5	Oshogbo	Jebba TS	0.5141	22
New Haven	Onitsha	1.0168	6	Shiroro	Katampe	0.5053	23
Okpai	Calabar	1.0000	7	Delta	Benin	0.5037	24
Alaoji	Onitsha	0.9972	8	Akangba	Ikeja West	0.5012	25
Alaoji	Calabar	0.9932	9	Egbin	Aja	0.5008	26
Delta	Aladja	0.8630	10	Ajaokuta	Benin	0.5005	27
Shiroro	Jebba TS	0.7712	11	AES	Ikeja West	0.5000	28
Benin	Omotoso	0.7568	12	Afam	Alaoji	0.5000	29

Egbin	Ikeja West	0.7498	13	Jebba GS	Jebb TS	0.5000	30
Aiyede	Oshogbo	0.7453	14	Ikeja West	Oshogbo	0.4944	31
Shiroro	Kaduna	0.7280	15	Ikeja West	Aiyede	0.4324	32
Sapele	Aladja	0.7142	16	Sapele	Benin	0.3081	33
Ikeja West	Papalanto	0.6977	17	Ikeja West	Benin	0.2085	34

V. CONCLUSION

In this article, a new approach to evaluate the power system transmission line resilience and vulnerability to the variation of increased power generation and loading is investigated using 330 kV, 30-bus Nigerian power system. The 330 kV, 30-bus, Nigerian transmission lines are often overstressed due to more than enough generation unit. This condition of operation is abnormal for power system operation. The PTDFI technique has the ability to monitor a quite number of network transmission lines, which have significant influence on the network operation in avoiding the network line overloading to enhance the transmission line resilience for sustainable uninterruptible power supply. The applicability of the proposed PTDFI model to the sample network serves as a reliable pointer to ranking the transmission lines. Also, this model serves as a useful tool in making faster decisions for proper transmission network expansion for sustainable power system operation.

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