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ORIGINAL RESEARCH ARTICLE

TRANSMISSION EXPANSION PROGRAMME FOR ELECTRIC NETWORK REINFORCEMENT

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ABSTRACT

Due to the increase in electricity demand, transmission sector has become overstressed since it can only be built at vast cost. In many developing economies, the network is highly susceptible to outages, collapse as well as partial or total failures, since the existing transmission capacity limit is often closely approached. To overcome this challenge better transmission expansion needs to be considered. This paper identified the implementation of transmission expansion with a number of creative approaches for overcoming network collapse in poor economy. The study deployed the application of improved Strength Pareto Evolution Algorithm (SPEA-2) optimization approach for solving the transmission expansion problem based on a simple power flow model. This model was deployed for running the Nigeria-31-bus system; to serve as the benchmark hence the standard IEEE 30-bus system was also considered. Using the traditional approach, the results obtained from the power flow analysis revealed that there are four major buses that recorded very high severity of violation. These were Jos, Kaduna, Kano and Birnin-Kebbi buses. In furtherance to this, additional effort was made to establish these findings by adapting the contingency analysis tests which provided more information on the earlier results so as to establish that these buses made the adjoining transmission lines connecting them to be identified as weak. Thus this serves as the contributory factor to the violation experienced by the entire the power network. For a more creative vivid display of the results; the Powerworld software was engaged for the analysis of the existing Nigeria-31 bus system while the violated buses that require more energy flow were provided with double circuit. This, thus, resulted in improved power outflow and inflow to the buses which led to the reduction of losses in the network. In conclusion, this study established that the transmission line connecting the geographical northern and southern parts of Nigeria dissipated quantifiably large value of losses which is mainly due to the nature and length of the line linking the source of electricity supply to a number of the load centres in the farther part of the country. Hence, it is suggested that the transmission expansion programme should be adopted for the improvement of power flow quantity which will, on the long run, reduce the power loss suffer by the existing network.

1.0 Introduction

Electric power transmission is the long-distance transfer of electrical energy from where it was generated to where it is consumed. Electricity is successively delivered to consumers through the distribution networks. The transmission grid is therefore the basic infrastructure that permits large physical power flow in a power system operation. Therefore, Transmission Expansion Programme (TEP), which decides which new lines will enable the system to satisfy future loads with the required degree of reliability is one of the main strategic decisions in power systems operation (Levi and Calovic, 1993).

The problem of inadequate power supply can be tackled by generation upgrade and/or expansion. This means that more generating units are added to the existing power plants or new power plants are built at new locations in a nation's power grid. Further generation always results in increased power flow on transmission lines connecting the grid. If the present transmission network is not capable of transferring this added generation, then an improvement or expansion of the transmission system is needed (Levi and Calovic, 1993).

In respect of Nigeria, the electric power system is continually undergoing metamorphosis due to steady increase in installation/commission of new power generating projects with little no improvement in the power grid. So, in most cases, the system fails to maintain its stability when there is a sudden outage of one of its components. This always affects the power quality delivered by the system. In a typical power system, the supply of electricity to load centres is as a result of the system operation that involves three stages namely: : the generated power at the generating stations which is thus transferred to the distribution centres through the high voltage transmission network. At the distribution station, the electrical power is derated to a lower voltage level to serve low voltage consumers. Due to the rising electricity consumption and expected renewable energy integration, transmission network expansion planning is required to help provide alternative paths for power transfer from power plants to load centres during emergencies. For improved power delivery in the nation; this expansion programme needs to be incorporated to the existing power system operation.

Fundamentally, the transmission network expansion planning is defined as the problem technical approach for determining the optimal location of new transmission lines within an existing grid in order to enhance power transfer. This helps in complementing the grid rehabilitation exercise for fast-tracking power sector recovery to ensure that the growing national electricity demand is met at the lowest economic cost. This is better achieved through mathematical modelling that is based on the optimization approach. There are different forms of Optimization techniques which have been lately adopted in solving the transmission expansion planning. This includes but not limited to the following, namely: linear programming (Levi and Calovic, 1993), Bendersde composition (Pereira, *et al.* 1985), branch and bound (Haffner, *et al.* 2001), Genetic Algorithm (Jingdong and Guoqing, 1997), simulated annealing (Romero, *et al.* 1996), etc.

The purpose of the transmission expansion planning problem programme is to propose the least economic cost transmission expansion strategy while fulfilling all the operation and security constraints of the power system operation. For the purpose of developing an effective transmission expansion network; the optimal decision on the location of the proposed new transmission lines is best obtained by modelling the system with the help of robust mathematically designed optimization technique. This procedure would involve the dynamic determination of the best combination of the conflicting goals/objectives desired for optimization in the presence of a number of trade-offs for the purpose of identifying the optimal location of the proposed new lines through adequate modelling, development and evaluation of the existing transmission network parameters.

2. Materials and Methods

The materials for the analysis of transmission expansion programme were variously ranging from the data gathered from the Transmission Company of Nigeria (TCN) on the Nigeria-31 bus system as well as the data of the IEEE-30 bus test case as obtained from the e-laboratory webpage of the Department of Electrical and Computer Engineering of the University of Washington. So also, the deployment of the power flow features of the Powerworld software for pictorial display of load flow analysis, and the use of the MATLAB software for the mathematical analysis.

2.1 Implementation of the Improved Strength Pareto Evolution Algorithm (SPEA-2)

With a solid inspiration from other forms of the evolutionary algorithm, two researchers Zitzler and Thiele (1999) developed the SPEA as a multi-objective optimization solution approach (Zitzler and Thiele, 1999). Few years later, this method was later improved to provide a better approach known as the improved SPEA (normally referred to as SPEA 2) approach (Zitzler, *et al.* 2002). The later tries to overcome the weaknesses of the later. Some of the weaknesses in the SPEA are that the fitness assignment scheme doesn't individuals that it dominates and dominated by, so also no strict guidance of the search process and the boundary solutions are highly threatened that there is high degree of failure to account for them in the final evaluation of best solutions. Fortunately, all the aforementioned setback are addressed in the SPEA-2.

In other words, the SPEA-2 uses a regular population and an archive (external set). Starting with an initial population and an empty archive the following steps are performed per iteration: First, all non-dominated population members are copied to the archive; in which case any dominated individuals or duplicates (regarding the objective values) are removed from the archive during this updated operation. However if the size of the updated archive exceeds a predefined limit, further archive members are deleted by a clustering technique which preserves the characteristics of the non-dominated front. Afterwards, fitness values are assigned to both archive and population members with the help of the following steps:

Each individual i in the archive is assigned a strength value $S(i)$, which at the same time represents its fitness value $F(i)$. $S(i)$ are the numbers of population members (i.e. j) that are dominated by or equal to individuals in the archive (i.e. i) with respect to the objective values, divided by the population size plus '1'.

The fitness $F(j)$ of an individual 'j' in the population is calculated by summing the strength values $S(i)$ of all archive members 'i' that dominate or are equal to 'j'; and adding '1' at the end.

The next step represents the mating selection phase where individuals from the union of population and archive are selected by means of binary tournaments. It should be noted that fitness is to be minimized here, hence each individual in the archive has a higher chance to be selected than any other population member. Finally, after recombination and mutation the old population is replaced by the resulting offspring population. To avoid the situation whereby the individuals dominated by the same archive members have identical fitness values, thus as stated

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earlier on; the beauty of the SPEA-2 is that for each individual; both dominating and dominated solutions are taken into account. In detail, each individual '' in the archive P_t and the population P_t is assigned a strength value $S(i)$, representing the number of solutions it dominates; thus as earlier stated, the SPEA-2 algorithm helps in the following ways, namely: the number of individuals contained in the archive is constant over a period of time of operation, and the truncation method prevents boundary solutions being removed.

During the process of environmental selection, the first step is to copy all non-dominated individuals, i.e., those which have fitness lower than unity from archive and population size to the archive of the next generation. The following should be noted in developing this algorithm (Abido, 2006):

Input: N (population size), N (archive size), T (maximum number of generations), Output: A (non-dominated set).

To facilitate this procedure in the work herein presented; thus the algorithm is executed in a step-by-step approach as follows:

Step 1

Initialization: Generate an initial population P_t and create the empty archive (external set) P_0 = ( ); .Set t = 0.

Step 2

Fitness assignment: Calculate fitness value of individual P_t

Step 3

Environmental selection: Copy all non-dominated individuals in P_t to P_{t+1} . If size of P_{t+1} exceeds N then reduce P_{t+1} by means of the truncation operator, otherwise if size of P_{t+1} is less than N then fill P_{t+1} with dominated individual in P_t and P_t .

Step 4

Termination: If t >T or another stopping criterion is satisfied then add set A to the set of decision vectors represented by the non-dominated individuals.

Step 5

Mating selection: Perform binary tournament selection with replacement on P_t >1 in order to fill the mating pool.

Step 6

Variation: Apply recombination and mutation operators to the mating pool and set P_{t+1} to the resulting population. Increment generation counter (t =t + 1) and go to Step 2.

In this research; the improved strength pareto evolution algorithm (SPEA-2) as a multiple objective function technique, as introduced above, is implemented. It should be noted that this approach involves solving a multi-criteria decision making complex problem moderated with the help of relevant trade-offs. In this study, the decision making involves the following objective functions namely: power loss, relevant cost (comprising reactive power support and fuel cost) and capital investment cost.

This can thus the power loss and cost can be modelled as shown in equation (1) and equation (2):

For the power loss,

$$F\left(x,z\right)=min\left(P_{loss}\right) \tag{1}$$

So also for the cost of fuel and reactive support;

$$Min\left(cost\right) = MinC_{gi}^{S}(S_{gi}^{\max}) \tag{2}$$

Equation (2) is simplified as the combination of reactive power support and fuel cost as depicted in equation (3)

i.e. $$MinC_{gi}^{s}(S_{gi}^{\max}) = C_{gi}^{q}(Q_{gi}^{\max}) + \tau_{gi}^{\max} C_{gi}^{p}(P_{gi}^{\max}) \tag{3}$$

Equations (1) and (2) are subjected to inequality constraints as shown in equations (4) and (5), i.e.:

$$V_{i,\min} \le \left|V_i\right| \le V_{i\max} \tag{4}$$

$$Q_{gi,\max} \le Q_{gi} \le Q_{gi,\max} \tag{5}$$

In the case of the investment in new transmission line; then equation (6) was adopted; thus the Capital Investment Cost (i.e. IN):

$$IN = \sum (1+r)^{-r-1} fc \times d_{ik} \times Z_{ik} + \sum_{k=1}^{n}\left(a_k P_{gk}^{2} + b_k P_{gk} + C_k\right) \tag{6}$$

While the general line impedance equation is given in equation (7);

$$Z_{ik} = R_{ik} + jX_{ik} \tag{7}$$

Where

Rik:=Resistance of the line to be expanded

Xik:=Reactance of the line to be expanded

dik:=Distance between adjacent buses of the transmission lines of interest.

fc:=Capital cost of building a transmission line per km($/km)

To calculate the capital investment cost or value, IN, the simple interest formular for determining the rate paid on invested principal value is obtained in equation (8)

r:=Interest rate, $$r = \frac{100(IN)}{PT} \tag{8}$$

T:= number of time periods

P:= principal amount of money to be invested

IN:= Capital Investment cost or value

a_k, b_k, c_k := Constant coefficient of generators

Thus Pgk as the active power generation of the k generating units subjected to

Active power balance constraint is obtained as in equation (9);

$$\sum_{k\in\lambda_i} P_{gk} = P_i + P_{di} \tag{9}$$

Where

$P_{di} :=$ Active power demand at bus, i $P_i :=$ Net active power injection at bus i

$P_{gk} :=$ Net active power flowing out of various buses into bus i

$k \in \lambda_i :=$ Total number of buses transmitting power into bus i

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2.2 Power flow model

The adopted modelling approach is the establishment of nonlinear relationship among the critical system parameters such as the bus power injection; as shown in equation (10), the branch power flow is as displayed in equation (11). So also, the bus voltages are as presented in equation (12) and the voltage angles which is as expressed in equation (13). So also the expression for line admittance is as shown in equation (14). . From the foregoing therefore; the power flow model which supplies information on the electrical performance of the lines with respect to the actual power flow in the various lines is thus presented as depicted in equation (15). This thus provides the needed information about the line loading capacity is as introduced in equations (16) and (17).. In developing power flow equations, it should noted that the balanced 3-phase system operation is assumed; hence per-phase analysis is utilized to obtain the relevant equations.

$$S_i = S_{gi} - S_{di} \tag{10}$$

$$S_i = V_i I_i^* = V_i \sum_{k=1}^{n} Y_{ik}^* V_k^* = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\cos\theta_{ik} + jB_{ik}\sin\theta_{ik}) \tag{11}$$

$$V_i = |V_i|\angle\theta_{ik} = |V_i|e^{j\theta_{ik}} \tag{12}$$

$$\theta_{ik} = \theta_i - \theta_k \tag{13}$$

$$Y_{ik} = G_{ik} + jB_{ik} \tag{14}$$

$$S_i = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\sin\theta_{ik} + jB_{ik}\sin\theta_{ik}) \tag{15}$$

$$P_i = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\sin\theta_{ik} + B_{ik}\sin\theta_{ik}) \tag{16}$$

$$Q_i = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\sin\theta_{ik}) \tag{17}$$

where

n:=total number of buses in the system

Pi and Qi:=specified active and reactive demand at load bus i

Gik:= element of line conductance

Bij:= element of line susceptance

θij:= phase angle between sending end voltage and receiving end voltage

$|V_i|$:= bus voltage at bus i;

$|V_j|$:= bus voltage at bus j;

Contingency analysis

The term contingencies are defined as potentially harmful disturbances that occur during the steady state operation of a power system. Load flow constitutes the most important study in a power system for planning, operation and expansion. The purpose of load flow study is to compute operating conditions of the power system under steady state. These operating conditions are normally voltage magnitudes and phase angles at different buses, line flows (MW and MVAR), real and reactive power supplied by the generators and power loss (Ezechukwu, 2013).

The contingency analysis is becoming an essential task for power system planning and operation. Thus the power system security analysis forms an integral part of modern energy management system. In other words, the power system security, as a term, is used for expressing the power systems ability to meet its load without unduly stressing its apparatus or allowing variables to stray from prescribed range under the apparatus or allowing variables to stray from prescribed range under certain pre-specified credible contingencies.

Hence in order to predict the effect of outages; the contingency analysis approach is widely embraced. This is predictably achieved by appealing to the contingency ranking protocol. This is best developed by determining, in descending order, the contingency ranking line severity index. This is the measurement of the effect of contingency event on the power system. The evaluation of the contingency effect is thus obtained in the off-line mode suing the earlier developed power flow model (as expressed in equations 10 to 14).

The violation of the line active power index is expressed as equation 15:

$$\varpi_p = \sum_{i=1}^{n} \frac{P_i}{P_{i\max}} \tag{15}$$

Where Pi := active power flow in line i

Pimax:= maximum active power flow in line i

So also the violation voltage violation is obtained as in equation (16);

$$\varpi_v = \sum_{i=1}^{n-m-1} \left(\frac{2(V_i - V_{io})}{V_{i\max} - V_{i\min}} \right) \tag{16}$$

Where n-m-1:= total number of load buses

m:= number of PV buses

n:= total number of load buses

Vi:= voltage at bus i

Vio:= nominal voltage at bus, i (i.e. 1p.u.)

Vimin:= minimum voltage limit (95% of Vio)

Vimax:= maximum voltage limit (105% of Vio)

It should be noted that this analysis is very apt in determining the state of robustness of a transmission network. In other words, the higher the value of severity indices (in equations (15) and equation (16)), the more the threats of the possibility of potential collapse of the system. Thus the value obtained has measurable tendency for predicting the necessity for the importunity of the transmission expansion programme.

3. Results and Discussion

From the foregoing methodology; a set of numerical results is then obtained by implementing the Powerworld software and MATLAB software. Thus, Table 1 shows the results obtained from the power flow analysis using the Newton Raphson load flow iteration method. This is then applied to the Nigeria-31 bus system by using the bus and line data gathered from the Transmission Company of Nigeria. Thus it presents the voltage profile of the Nigeria-31 bus system in which the generation buses within the network are seven in number with one of them

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serving as the slack bus for the network. To further appreciate the foregoing; the appropriate equations derived in the preceding sections were then applied on the electrical loading capacity of the various lines. Further investigation was also performed on the Nigeria-31 bus system to evaluate the single line contingency test. The summary of the contingency analysis was showcased in the succeeding graphs and tables.

Whereby the voltage profile is as presented in Table 1, this vividly shows at a glance the lines and buses that need attention of the network planners. From Table 1, it is clearly evident that a number of buses violated the $\pm 5\%$ boundary set for the operation of power system; such buses are Bus Number: 2, 10, 13, 14, 15, 16, 17, 18, 19, 20, 22, 23, 24, 25 and 28. It must be noted that at the verge of violation is found Bus Number: 5.

In the case of Table 2; for the Nigeria-31 bus system, the lines that are highly threatened due to the line losses is arranged in the order severity are Lines: 9-11, 29-12, 8-15, 10-15 and 18-12.

Table 1: Voltage profile of the Nigeria-31 bus system

Loading and generation of network including bus voltage and angle								
Bus No	V (pu)	Angle	Injection		Generation		Load	
		(Degree)	MW	MVar	MW	MVar	MW	Mvar
1	1.020	0.000	825.461	332.244	825.461	332.244	0.000	0.000
2	0.990	-2.956	200.000	-43.876	200.000	-43.876	0.000	0.000
3	1.000	-2.382	300.000	11.300	300.000	11.300	0.000	0.000
4	1.000	-8.914	250.000	138.405	250.000	138.405	0.000	0.000
5	1.030	7.076	490.000	-52.650	490.000	-52.650	0.000	0.000
6	1.040	7.387	350.000	-27.038	350.000	-27.038	0.000	0.000
7	1.030	9.587	450.000	-35.419	450.000	-35.419	0.000	0.000
8	0.995	-5.036	-156.000	-79.900	0.000	0.000	156.000	79.900
9	1.040	4.645	-8.600	-5.600	0.000	0.000	8.600	5.600
10	0.982	-5.693	-429.900	-258.400	0.000	0.000	429.900	258.400
11	1.016	-0.557	-201.000	-136.700	0.000	0.000	201.000	136.700
12	1.034	-1.170	-166.200	-97.800	0.000	0.000	166.200	97.800
13	1.063	-6.450	-58.400	-28.400	0.000	0.000	58.400	28.400
14	0.978	-11.259	-144.700	-88.400	0.000	0.000	144.700	88.400
15	0.973	-10.828	-115.200	-42.000	0.000	0.000	115.200	42.000
16	0.996	-4.827	-82.100	-44.500	0.000	0.000	82.100	44.500
17	0.958	-12.711	-112.600	-50.000	0.000	0.000	112.600	50.000
18	0.994	-8.084	-184.900	-60.000	0.000	0.000	184.900	60.000
19	1.075	-10.670	-102.900	-17.500	0.000	0.000	102.900	17.500
20	1.021	2.030	-60.300	-70.000	0.000	0.000	60.300	70.000
21	1.006	-6.017	-26.800	-10.500	0.000	0.000	26.800	10.500
22	0.978	-6.133	-292.000	-114.900	0.000	0.000	292.000	114.900
23	0.998	-3.220	-193.500	-101.200	0.000	0.000	193.500	101.200

24	0.993	-4.123	-139.400	-61.000	0.000	0.000	139.400	61.000
25	1.000	-3.005	-109.700	-64.200	0.000	0.000	109.700	64.200
26	0.996	-4.356	0.000	0.000	0.000	0.000	0.000	0.000
27	0.999	-4.675	-64.300	-44.200	0.000	0.000	64.300	44.200
28	0.981	-10.991	-119.300	-65.700	0.000	0.000	119.300	65.700
29	1.041	2.785	-61.500	-10.300	0.000	0.000	61.500	10.300
30	1.045	4.892	0.000	0.000	0.000	0.000	0.000	0.000
31	1.040	4.932	0.000	0.000	0.000	0.000	0.000	0.000

In the case of Table 2; for the Nigeria-31 bus system, the lines that are highly threatened due to the line losses is arranged in the order severity are Lines: 9-11, 29-12, 8-15, 10-15 and 18-12.

Table 2: Line flow and Line loss of the Nigeria-31 bus transmission line

From Bus	To Bus	P (MW)	Q (Mvar)	From Bus	To Bus	P (MW)	Q (Mvar)	Line Loss (MW)	(Mvar)
25	1	-825.940	-242.193	1	25	825.940	291.920	0.000	49.727
26	2	-200.000	35.026	2	26	200.000	-30.002	0.000	5.024
27	3	-300.000	-15.482	3	27	300.000	27.581	0.000	12.099
28	4	-250.000	-129.449	4	28	250.000	141.171	0.000	11.722
29	5	-490.000	86.333	5	29	490.000	-48.893	0.000	37.440
30	6	-350.000	30.718	6	30	350.000	-15.387	0.000	15.331
31	7	-450.000	63.900	7	31	450.000	-26.891	0.000	37.009
10	8	-31.213	-54.646	8	10	31.445	56.397	0.232	1.751
11	8	109.331	14.496	8	11	-108.156	-5.665	1.175	8.831
8	15	245.872	32.086	15	8	-242.515	-6.816	3.357	25.270
21	8	-26.800	22.002	8	21	26.892	-21.313	0.092	0.689
8	26	-155.680	4.482	26	8	155.889	-2.663	0.209	1.819
8	27	-196.404	59.991	27	8	197.633	-59.109	1.229	0.882
9	11	633.489	129.221	11	9	-625.505	-69.260	7.984	59.961
9	29	95.623	-17.475	29	9	-95.202	20.634	0.421	3.159
30	9	289.242	6.360	9	30	-288.018	-5.137	1.224	1.223
31	9	450.000	-61.006	9	31	-449.694	63.263	0.306	2.257
11	10	105.643	40.585	10	11	-104.185	-29.618	1.458	10.967
10	22	292.377	112.165	22	10	-292.000	-109.378	0.377	2.787
24	10	68.176	30.731	10	24	-67.865	-28.390	0.311	2.341
10	25	-519.014	-77.597	25	10	522.604	104.548	3.590	26.951
11	24	209.531	67.682	24	11	-207.576	-52.983	1.955	14.699
12	13	164.637	-65.939	13	12	-162.356	83.129	2.281	17.190
18	12	-184.900	-22.413	12	18	188.078	46.318	3.178	23.905
29	12	523.702	4.711	12	29	-518.916	31.226	4.786	35.937
13	19	103.956	-25.158	19	13	-102.900	33.097	1.056	7.939

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15	14	14.140	-14.523	14	15	-14.113	14.722	0.027	0.199
14	28	-130.587	-70.858	28	14	130.700	71.711	0.113	0.853
15	17	113.175	39.805	17	15	-112.600	-35.475	0.575	4.330
26	16	44.111	-5.689	16	26	-44.061	6.061	0.050	0.372
27	16	38.067	36.211	16	27	-38.039	-35.998	0.028	0.213
20	30	-60.300	-16.630	30	20	60.758	20.079	0.458	3.449
25	23	193.636	97.753	23	25	-193.500	-96.744	0.136	1.009

3.1 Pareto space

According to Table 3 as regards the implementation of the improved strength pareto evolutionary algorithm (SPEA-2), it can be seen that the adopted number of generation (i.e. the previous generation from which the next parent for current generation are chosen) was 200 while the size of archive (externally stored pareto solution) was 50 and the population size was 250. Whenever this is implemented; it resulted in the convergence to a pareto front as will be displayed in a number of scenarios that would later be presented in this study.

Table 3: Improved Strength Pareto Evolution Algorithm parameters

Generation	200
Archive Set	50
Population size	250

3.2 Optimal Solution

As stated earlier, there is need in decision making to consider trade-offs due to conflicting goals that must be optimized in the application of the optimization theory. In the case of this research work, the three parameters of interest are namely; the line index, power losses and capital investment cost needed for the expansion of the network; in order to alleviate the challenges of outages that are necessitated by weak links as presented in the violated lines. In order to have a better understanding of this, using the SPEA-2 the Nigeria-31 bus system is compared with a standard benchmark as represented by IEEE-30 bus system. Thus, the outcome of this led to the results displayed in Figures 1 and 2 in which the power loss was compared with the power generation cost for both bus systems. From the available details in both diagrams; the results of the IEEE-30 bus is quite optimal in outlook while that of the Nigeria-31 bus system is highly violated hence there is need for capital-intensive investment; i.e. using the transmission expansion as a formidable option; to ensure that the power loss is reduced drastically so as to be more competitive to the IEEE-30 bus system.

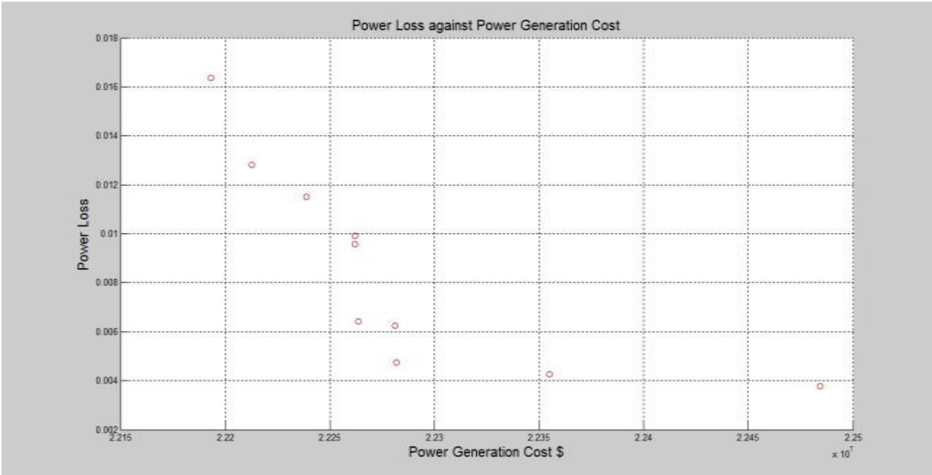

Figure 1: Nigeria 31-bus Pareto front for Power loss against Power generation cost

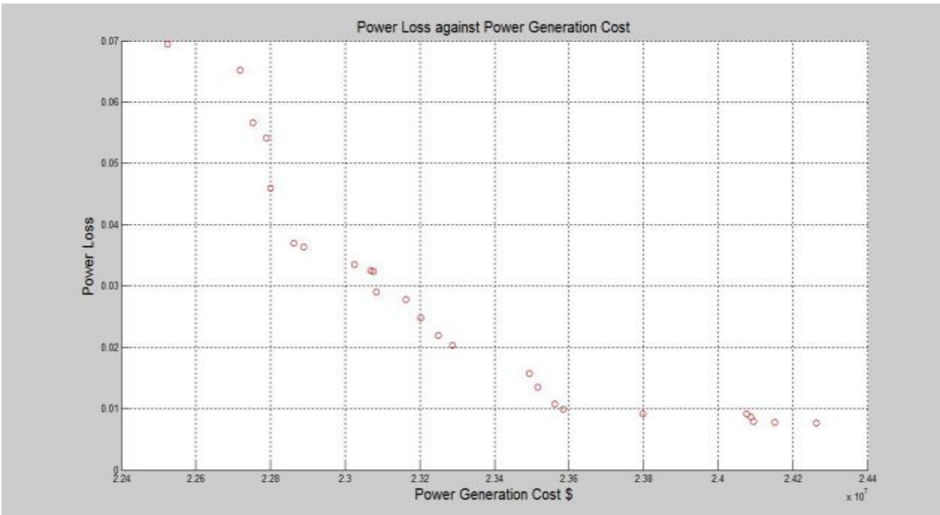

Figure 2: IEEE 30-bus Pareto front for Power loss against Power generation cost

3.3 Transmission expansion philosophy

With reference to previous discussion, from the output of the earlier considered graphs; it's very essential to consider the power loss against investment cost. This would provide information on the extent to which the transmission network needs to be upgraded to avoid incessant outages (which is currently very prevalent). Thus, since a number of lines has been discovered as the weakest link in the energy flow chain of the Nigeria-31 bus system hence there is need to reinforce the network to overcome the influence of voltage collapse through the threats emanating from these identified buses on the network. In this vein, Figure 3 shows the investment cost as compared with the power loss. Thus if this investment well managed at critical buses then the network will experience a better power flow.

In line with the multi-objective solution philosophy of transmission expansion programme, thus the Nigeria-31 bus system was subjected to a three-objective function. With the help of the SPEA-2; this results in the generation of the results that displayed in Figure 4. This thus corroborates the propensity of the well-planned transmission expansion programme as a last resort of the current energy crisisthat is bedeviling the Nigeria electricity industry.

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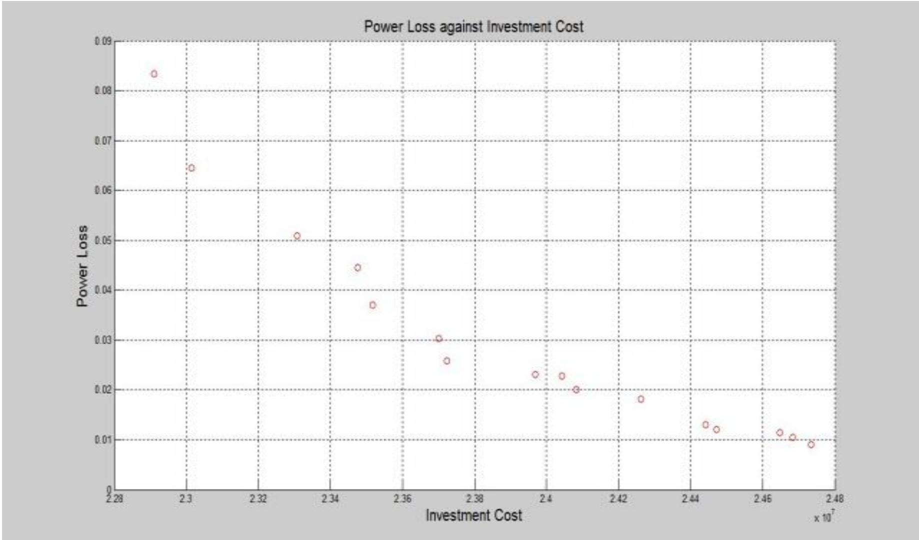

Figure 3: Pareto front for Power loss against investment cost

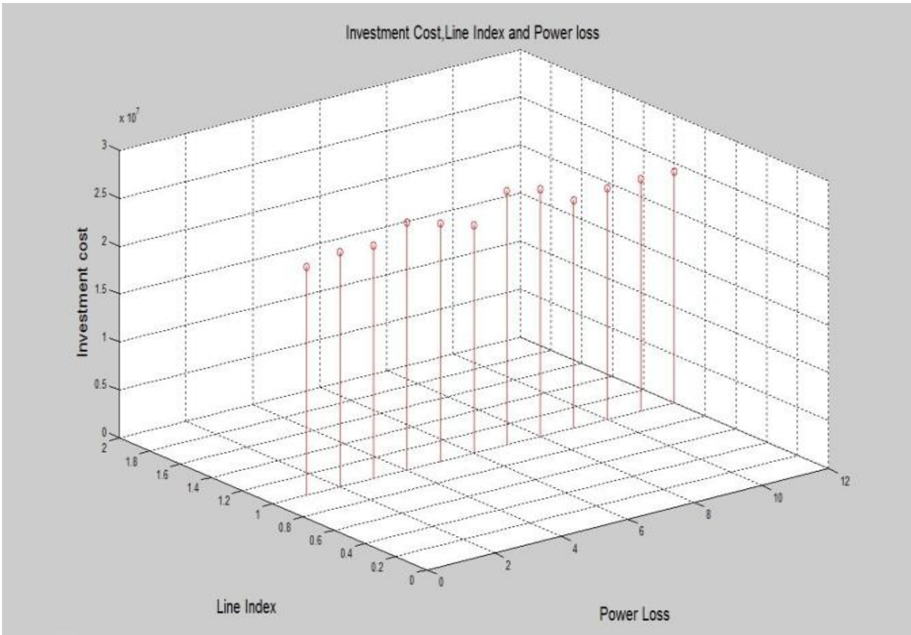

Figure 4: Pareto front for Investment cost, Line Index and Power loss

3.4 Results of the contingency analysis of the Nigeria-31 bus network

To achieve the contingency analysis, the lines or generators were carefully chosen and then remove from service for the purpose of subjecting the network to contingency test. In this case only one line is taken out of service in each scenario as shown in Table 5.

Thus, from the foregoing, this shows that when the generators were subjected to contingency test, with one of the generators shutdown, it gave rise to cascaded violation of the network. It can be seen from this table that when contingency analysis was performed on the network; the buses that the buses that suffered major violation were: the buses located at Jos (i.e. Bus 14), Gombe (i.e. Bus 17), Birnin Kebbi (i.e. Bus 28) and Kaduna (i.e. Bus 29). Obviously, this is due to a number of factors among which are the distance and source of power generation to these buses. So also lack of transmission line reinforcement using the power conditioners (such as the bank of reactors, shunt power electronics devices) at the identified buses are all contributory indices to the violation suffered by the lines during this contingency test. However, with the introduction of the new generation at Geregu and Ajaokuta, it is expected that it will relieve the buses in the network around this section of the transmission network.

Table 4: Single transmission line contingency test

Contigency Considered	Skip	Processed	Solved	Violations
Line from 11 (Benin) to 2 (DeltaPs) C1	NO	YES	YES	4
Line from 2 (DeltaPs) to 21 (Aladja) C1	NO	YES	YES	4
Line from 15 (Onitsha) to 3 (Okpai) C1	NO	YES	YES	5
Line from 11 (Benin) to 4 (Sapele) C1	NO	YES	YES	4
Line from 4 (Sapele) to 21 (Aladja) C1	NO	YES	YES	4
Line from 26 (Alaoji) to 5 (Afam) C1	NO	YES	YES	4
Line from 10 (Oshogbo) to 6 (Jebba) C1	NO	YES	YES	4
Line from 27 (JebbaTS) to 6 (Jebba) C1	NO	YES	NO	Unsolved
Line from 7 (Kainji) to 27 (JebbaTS) C1	NO	YES	YES	4
Line from 7 (Kainji) to 27 (JebbaTS) C2	NO	YES	YES	4
Line from 7 (Kainji) to 28 (B. Kebbi) C1	NO	YES	YES	3
Line from 27 (JebbaTS) to 8 (Shiroro) C1	NO	YES	NO	Unsolved
Line from 8 (Shiroro) to 30 (ShiroroTS) C1	NO	YES	NO	Unsolved
Line from 9 (Geregu) to 24 (Ajaokuta) C1	NO	YES	YES	4
Line from 10 (Oshogbo) to 11 (Benin) C1	NO	YES	YES	4
Line from 10 (Oshogbo) to 12 (Ikeja-West) C1	NO	YES	YES	4
Line from 13 (Ayede) to 10 (Oshogbo) C1	NO	YES	YES	4
Line from 12 (Ikeja-West) to 11 (Benin) C1	NO	YES	YES	4
Line from 11 (Benin) to 15 (Onitsha) C1	NO	YES	YES	4
Line from 11 (Benin) to 24 (Ajaokuta) C1	NO	YES	YES	4
Line from 13 (Ayede) to 12 (Ikeja-West) C1	NO	YES	YES	4
Line from 16 (Akangba) to 12 (Ikeja-West) C1	NO	YES	YES	5
Line from 32 (EgbinTS) to 12 (Ikeja-West) C1	NO	YES	NO	Unsolved
Line from 14 (Jos) to 17 (Gombe) C1	NO	YES	YES	2
Line from 29 (Kaduna) to 14 (Jos) C1	NO	YES	YES	4
Line from 15 (Onitsha) to 25 (N. Haven) C1	NO	YES	YES	4
Line from 15 (Onitsha) to 26 (Alaoji) C1	NO	YES	YES	4
Line from 30 (Shiroro TS) to 18 (Abuja) C1	NO	YES	YES	5
Line from 29 (Kaduna) to 22 (Kano)	NO	YES	NO	Unsolved
Line from 23 (Aja) to 32 (EgbinTS) C1	NO	YES	YES	4
Line from 23 (Aja) to 32 (EgbinTS) C2	NO	YES	YES	4
Line from 30 (ShiroroTS) to 29 (Kaduna) C1	NO	YES	YES	4
Line from 30 (ShiroroTS) to 29 (Kaduna) C2	NO	YES	YES	4
Line from 31 (EgbinPS) to 32 (EgbinTS) C1	NO	YES	NO	Unsolved

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Table 5: Summary of contingency analysis

Contigency Considered	Buses Violated
Line from 11 (Benin) to 2 (DeltaPs) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 2 (DeltaPs) to 21 (Aladja) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 15 (Onitsha) to 3 (Okpai) C1	Jos (14), Gombe (17), B. Kebbi (28), Kaduna (29) and N. Haven (25)
Line from 11 (Benin) to 4 (Sapele) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 4 (Sapele) to 21 (Aladja) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 26 (Alaoji) to 5 (Afam) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 10 (Oshogbo) to 6 (Jebba) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 7 (Kainji) to 27 (Jebba TS) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 7 (Kainji) to 27 (JebbaTS) C2	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 7 (Kainji) to 28 (B. Kebbi) C1	Jos (14), Gombe (17) and Kaduna (29)
Line from 9 (Geregu) to 24 (Ajaokuta) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 10 (Oshogbo) to 11 (Benin) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 10 (Oshogbo) to 12 (Ikeja-West) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 13 (Ayede) to 10 (Oshogbo) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 12 (Ikeja-West) to 11 (Benin) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 11 (Benin) to 15 (Onitsha) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 11 (Benin) to 24 (Ajaokuta) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 13 (Ayede) to 12 (Ikeja-West) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 16 (Akangba) to 12 (Ikeja-West) C1	Jos (14), Gombe (17), B. Kebbi (28), Kaduna (29) and Oshogbo (10)
Line from 14 (Jos) to 17 (Gombe) C1	Kano (22) and B. Kebbi (28)
Line from 29 (Kaduna) to 14 (Jos) C1	Abuja (18), Kano (22) B. Kebbi (28) and Kaduna (29)
Line from 15 (Onitsha) to 26 (Alaoji) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 15 (Onitsha) to 26 (Alaoji) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 30 (Shiroro TS) to 18 (Abuja) C1	Jos (14), Gombe (17), B. Kebbi (28), Kaduna (29) and ShiroroTS (30)
Line from 23 (Aja) to 32 (EgbinTS) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 23 (Aja) to 32 (EgbinTS) C2	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 30 (ShiroroTS) to 29 (Kaduna) C1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Line from 30 (ShiroroTS) to 29 (Kaduna) C2	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Generator 2 (DeltaPs) U1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Generator 3 (Okpai) U1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Generator 4 (Sapele) U1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)
Generator 5 (Afam) U1	Jos (14), Gombe (17), B. Kebbi (28) and Kaduna (29)

3.5 Power Flow analysis with Powerworld software

Furthermore, the same network data were subjected to the implementation of the the powerworld software to display the pictorial situation of the existing transmission network in the Nigeria-31 bus system so as to identify the area of improvement needed for the healthy operation of the network. The investigation is as displayed in Figure 5 whereby the existing power network of the Nigeria-31 bus system data were deployed for giving information on the existing state of the Nigeria's transmission network. Just as earlier declared by the traditional analysis approach that identified a number of buses are the weak links in the Nigeria's transmission network, the pictorial software further displays vividly the precarious state of power system operation in the Nigeria-31 bus system. This results further validate the earlier pronounced findings which identified the most violated buses as those situated at Kaduna, Gombe, Jos and Birnin Kebbi.

In anticipation of the solution, as a correction step, extra single line was introduced between Kanji bus and Birnin-Kebbi transmission bus while another line was introduced Shiroro and Abuja buses as well as an extra line along Kaduna to Jos bus; this leads to immense improvement in the power flow in the network, especially with regard to the identified weak buses, the power flow in them increased considerably as shown in Figure 6.

Thus it can be summarized that the existing Nigeria's transmission network needs the assistance of the double line as introduced in Figure 6. This is expected to bring about great improvement in the voltage profile which has a direct and constructive influence on the reliability of electricity supply within the Nigeria-31 bus system.

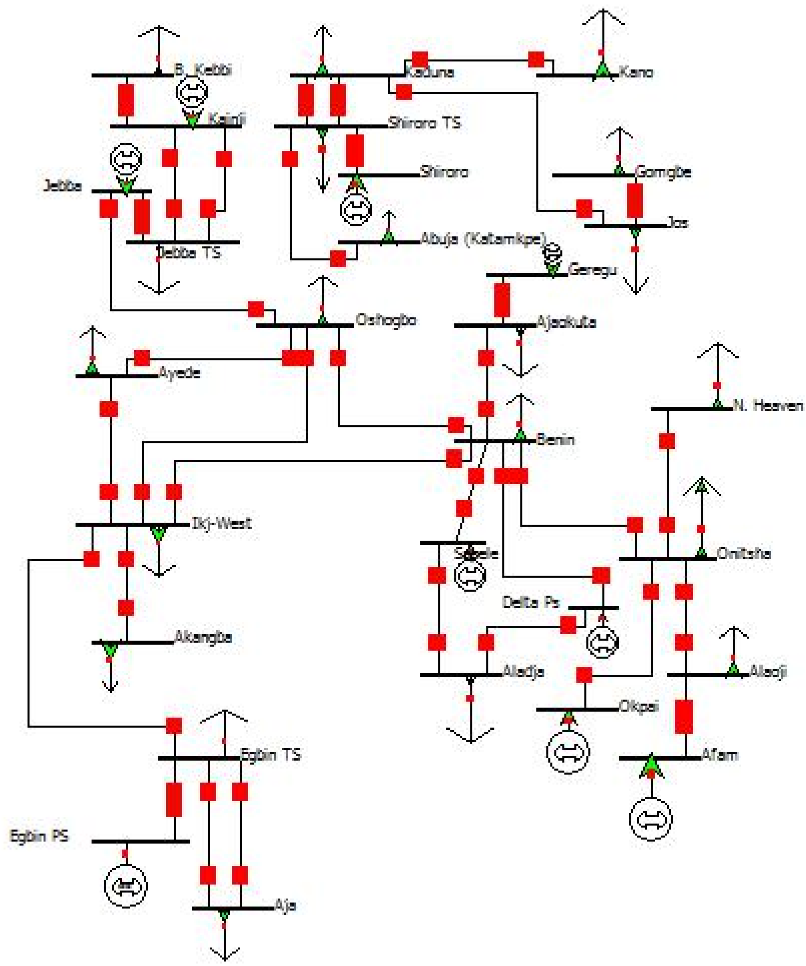

Figure 5: Existing Nigeria-31-bus Network

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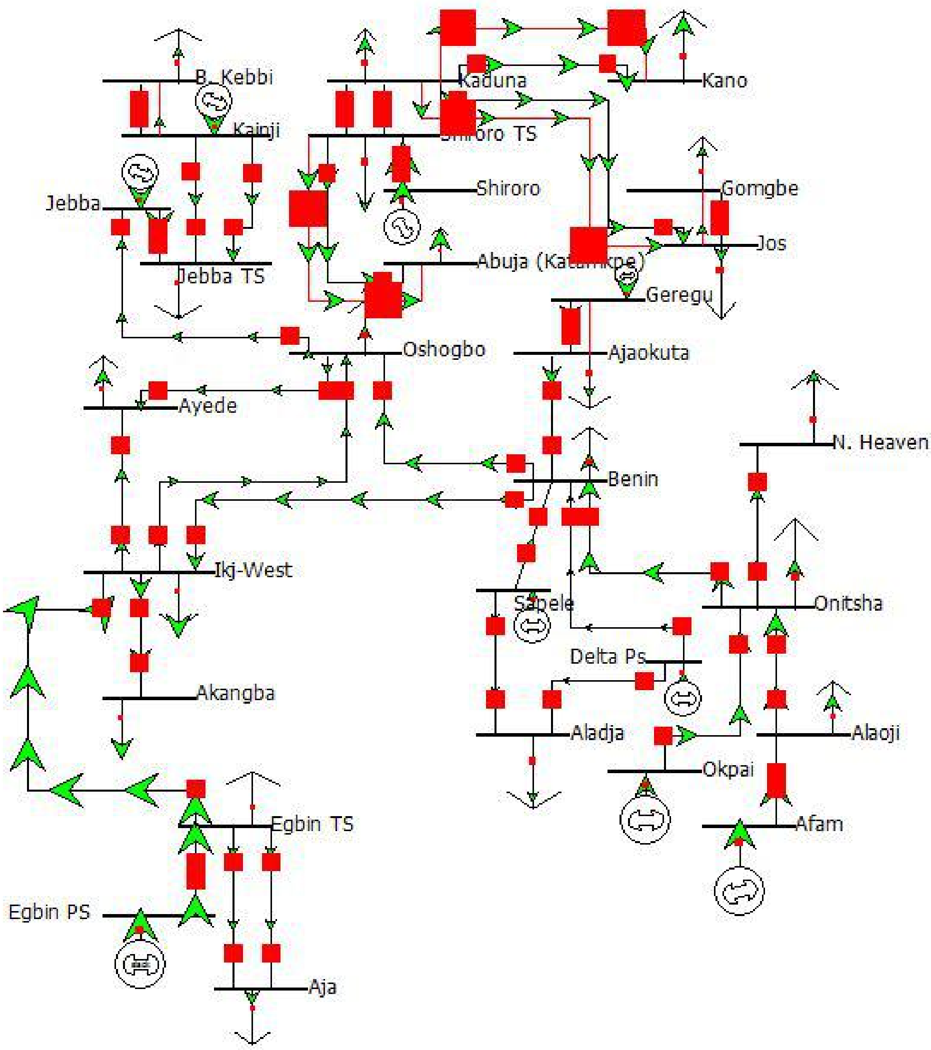

Figure 6: Improved Nigeria-31-bus transmission network

4. Conclusion

This study addressed the transmission system expansion planning using an optimization approach known as the improved Strength Pareto Evolution Algorithm (SPEA-2) while also using the contingency analysis to isolate the most threatened lines and buses in the Nigeria's transmission network. It was discovered that four major buses were violated which were located at Jos, Kaduna, Kano and Birnin-Kebbi respectively.

Suggestively, it was also observed during this research work that transmission lines linking the geographical northern and southern parts of Nigeria experienced more power losses than any others. This is believed to be due to the length of transmission lines which remained uncompensated by neither traditional bank of reactors nor the modern power electronics devices. . further to this, it was observed that when contingency test was applied to the same network; the Kano, Birnin-Kebbi, Kaduna and Gombe buses had the highest number of violation when transmission line were opened as well as while one of the generators was shutdown. This thus suggests that, with the addition of double circuit on each transmission line connected to the weak buses in the Nigeria-31 bus system, thus the violation was drastically reduced. Furthermore, with the implementation of the improved strength Pareto evolution algorithm (SPEA-2); it was possible to determine the optimal and best solution in terms of line index function, Investment cost analysis and the power loss protocol.

Thus the transmission expansion philosophy has shown a great potential for overcoming the identified congestion created by the weak transmission lines in the various locations. .

APPENDIX

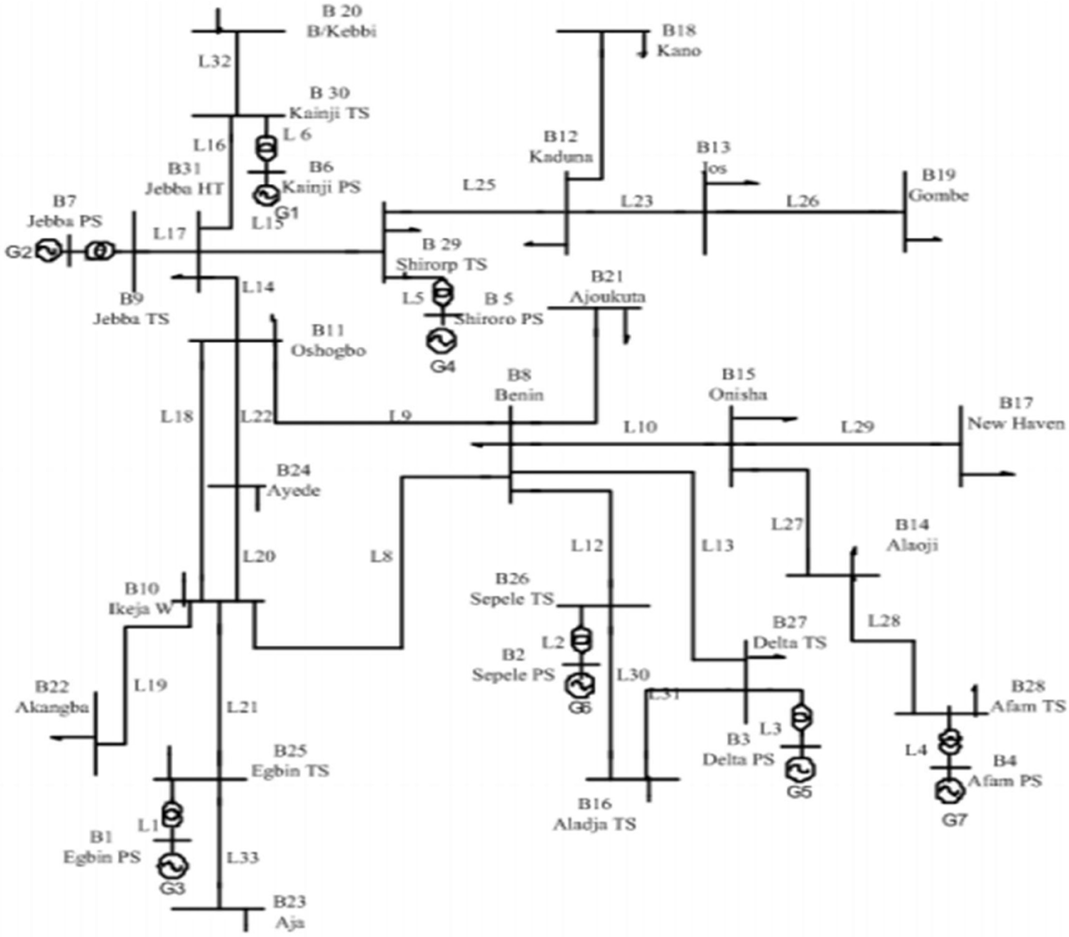

Figure 7: One line diagram of the Nigerian Transmission Network

Table 6: Generator Data of Nigerian 330 kV Grid System

Bus No	Pg (MW)	Qg (MVAr)	Qmax (MVAr)	Qmin (MVAr)	Base MVA	Vg (p.u.)
1	830.23	0	450	-255	100	1.00
2	200	0	450	-250	100	0.99
3	300	0	450	-250	100	1.00
4	250	0	450	-250	100	1.00
5	490	0	450	-250	100	1.03
6	350	0	450	-250	100	1.04
7	450	0	450	-250	100	1.03

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Table 7: Line Data of Nigerian 330 kV Grid System

From Bus	To Bus	R (p.u.)	X (p.u.)	0.5B (p.u.)
25	1	0	0.00648	0
26	2	0	0.01204	0
27	3	0	0.01333	0
28	4	0	0.01422	0
29	5	0	0.01638	0
30	6	0	0.01351	0
31	7	0	0.01932	0
10	8	0.0055	0.04139	0.9425
11	8	0.00987	0.07419	0.41575
8	15	0.00538	0.0405	0.2269
21	8	0.00766	0.05764	0.323
8	26	0.0003098	0.00739	0.16565
8	27	0. 00287	0.02158	0.1209
9	11	0.00206	0.01547	0.78
9	29	0.0048	0.03606	0.80825
30	9	0.00159	0.01197	0.2683
31	9	0.00016	0.00118	0.0265
11	10	0.01163	0.0875	0.49025
10	22	0.00036	0.00266	0.0595
24	10	0.00538	0.0405	0.227
10	25	0.00122	0.00916	0.2054
11	24	0.00412	0.03098	0.1736
12	13	0.00774	0.05832	0.3263
18	12	0.00904	0.06799	0.38095
29	12	0.00189	0.01419	0.318
13	19	0.01042	0.07833	0.4398
15	14	0.00605	0.04552	0.25505
14	28	0.00049	0.00369	0.0828
15	17	0.00377	0.02838	0.159
26	16	0.00248	0.01862	0.10435
27	16	0.00102	0.00769	0.043065
20	30	0.01218	0.09163	0.51345
25	23	0.00028	0.00207	0.0464

Table 8: Bus Data of Nigerian 330 kV Grid System

Bus No	Type	Pd (MW)	Qd (MVAr)	Base kV	Vmax (p.u.)	Vmin (p.u.)
1	1	0	0	16	1.1	0.9
2	2	0	0	16	1.1	0.9
3	2	0	0	16	1.1	0.9
4	2	0	0	16	1.1	0.9
5	2	0	0	16	1.1	0.9
6	2	0	0	16	1.1	0.9
7	2	0	0	16	1.1	0.9
8	0	156.8	79.9	330	1.1	0.9
9	0	8.6	5.6	330	1.1	0.9
10	0	429.9	58.4	330	1.1	0.9
11	0	201	136.7	330	1.1	0.9
12	0	166.2	97.8	330	1.1	0.9
13	0	58.4	28.4	330	1.1	0.9
14	0	144.7	88.4	330	1.1	0.9
15	0	155.2	42	330	1.1	0.9
16	0	82.1	44.5	330	1.1	0.9
17	0	112.6	50	330	1.1	0.9
18	0	184.9	60	330	1.1	0.9
19	0	102.9	17.5	330	1.1	0.9
20	0	60.3	70	330	1.1	0.9
21	0	26.8	10.5	330	1.1	0.9
22	0	292	114.9	330	1.1	0.9
23	0	193.5	101.2	330	1.1	0.9
24	0	139.4	61	330	1.1	0.9
25	0	109.7	64.2	330	1.1	0.9
26	0	0	0	330	1.1	0.9
27	0	64.3	44.2	330	1.1	0.9
28	0	119.3	65.7	330	1.1	0.9
29	0	61.5	10.3	330	1.1	0.9
30	0	0	0	330	1.1	0.9
31	0	0	0	330	1.1	0.9

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