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DEVELOPMENT OF OPTIMAL PLACEMENT OF DISTRIBUTED GENERATORS IN ELECTRICAL NETWORK USING IMPROVED STRENGTH PARETO EVOLUTIONARY ALGORITHM

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ABSTRACT

In recent times, the issue of the gap between electricity supply and demand has been addressed using distributed generation (DG) technology. When DG technology is properly placed within a transmission and distribution network, there is always improvement in power loss reduction, voltage profile and system reliability. Proper placement can be achieved by evaluating the optimal values for voltage deviation, real power loss and bus voltage. Thus, this study presents a multi-objective DG optimisation model that minimizes of voltage deviation and real power loss, while maximising voltage stability factor. The model was formulated as a multi-objective problem and solved using an improved Strength Pareto Evolutionary Algorithm (SPEA-2) technique of optimisation to DG problem. The Nigeria-31 bus, 330 KV, transmission network was considered as test case. The results obtained were validated with the standard IEEE 30-bus system. In addition, this study presented scenarios where 1, 2 and 3 DGs were placed into these test cases. Based on the SPEA-2 implementation, the optimisation run time for the Nigerian network and the IEEE network were 2229.55 and 2039.42 secs, respectively. The optimal bus location of the three DGs (whose capacities are: 8.7793 MW/6.1272 MVAr, 8.1806 MW/4.7778 MVAr and 7.9567 MW/4.6281 MVAr respectively) for the IEEE 30 bus were 5,7 and 26 buses, respectively, while for the Nigerian-31 bus were 14, 15 and 17 (whose capacities are: 22.9693 MW/15.2956 MVAr, 27.3711 MW/21.7274 MVAr and 30.9910 MW/15.4069 MVAr respectively) respectively. For the placement of these DGs, the power loss reduction in the IEEE-30 bus is 16.17 MW, 15.28 MW, 14.07 MW respectively and 64.21 MVAr, 61.19 MVAr, 56.13 MVAr respectively. While for the Nigeria-31 bus system; the reduction in power loss is: 34.66 MW, 33.99 MW, 33.82 MW and 411.85 MVAr, 403.45 MVAr, 400.54 MVAr respectively. The results obtained showed that the total power losses reduced as DGs are sited at the optimal locations for the two test cases when compared with cases when DGs were not considered.

Keywords: *Distributed generators, power loss, voltage profile, optimal placement, evolutionary algorithm.*

INTRODUCTION

It was established that the quantity of electricity demand in Nigeria far exceeds the quantity supplied (Awosope, 2003). Because of this, large industrial energy consumers are not supplied during periods of load-shedding (Nag, 2010). Hence captive generation is thus installed to meet up with the energy deficit though this has led to increase in air and noise pollution. However, Boor and Hosseini (2014) revealed that the Nigerian power system is highly unreliable due to long period of neglect of the electricity infrastructural development. This has too much loss which is now incurred as bulk power is transported through the weak and fragile transmission infrastructure. Hence, there is urgent demand for a medium-term solution to the problem of inadequate and unreliable electrical power in Nigeria (Boor and Hosseini, 2014). Therefore, this inspired the introduction of distributed generation to reinforce the network as a solution to this challenge.

In order to overcome this challenge, several techniques have been developed. But most of these methods are fraught with a number of setbacks (Awosope, 2003). Hence the use of distributed generation (DG) technology on transmission and distribution networks is currently being identified and studied by researchers as a means of closing the gap between supply and demand for electricity (Boor and Hosseini, 2014; Kumawat *et al*., 2015). The presence of DG in the power system has merits such as power loss reduction, voltage profile improvement, improved reliability etc. These advantages can only be exploited if the EGs are properly placed at various optimal buses in the power network; else their presence will cause negative effect on the network such as bidirectional power flow which affects voltage profile stability and poor quality of supply (Rau and Wan, 1994; Kashem and Ledwich, 2004).

Modern electric power system is required to have reasonable ability to satisfy the customer load demand (IEEE Report, 1978). Thus, the reliability is very essential to determine improvement in mean-time-between-failure (MTBF) so as to evaluate the strength of the network to provide longer hours of service before loss of supply (Rausand, 2004; Oluseyi *et al*., 2006). Other works have also considered the importance of the DGs in reinforcing the system against failure.

The work is extended to the distribution network. In this case the known parameters are optimized in which the optimization problem via Pareto optimal approach result in highlighting the technical and financial benefits of DGs sensitivity factor; this is best achieved by reducing the search space for the placement of distributed generators (Injeti, 2018; Ravindran and Victoire, 2018). Din, *et al*. (2019) furthers this study by considering the quality assessment of the power system after the identification of the optimal location and appropriate sizing of the DGs.

The aim of this study is to ensure optimal placement of DGs on Nigerian transmission network in order to improve the system reliability. This will be achieved by conducting a load flow studies on the Nigerian transmission network to identify the buses with poor voltage profile. DGs will then be placed at suitable buses using the Improved Strength Pareto Evolutionary Algorithm (SPEA-2) technique of optimisation.

The objectives of this study are to determine optimal locations of DGs on a distribution network using a SPEA-2 and to compare the total power loss of distribution network with and without DG.

Distributed Generation

The distributed generation (DG) is also known as embedded generation (EG), decentralised generation, dispersed generation, and on-site generation (Reddy, 2014; Kumawat *et al*., 2015; Georgilakis and Hatziargyriou, 2012). Due to the importance of the DG to the sustainable development goals, various authors and agencies have given different forms of definitions as regards the distributed generation. IEA (2002) defined as generating plant which serves a customer on-site or providing support to a distribution network, connected to the grid at distribution voltage level. The CIGRE (CIGRE, 1999) defined DG as the generation which ranges from 50-100 MW. This is usually connected to the distribution network, and is not centrally planned nor centrally dispatched. Ackermann *et al*., (2001) defined DG as generation from few kilowatts up to 50 MW. DG can also be defined as the generation of electric power by strategic installation of small or limited sized generating unit(s) at different locations within the power network (Reddy, 2014; Lai and Chan, 2007). The DG can be used for stand-alone operation to supply customer's power demand, or it can be connected to the grid to supply electrical power to the power system (Shrivastava *et al*., 2012).

In modern power system technology, dispersed generation has been seen to be an attractive energy resource and has attracted so much research attention. The ever increasing research attention on DG technology can be attributed to the potential benefits it presents to the energy crisis that has bedeviled so many developing countries including Nigeria (Abookazim *et al*., 2010). The DG sources are mostly small-scale technologies which have no negative effect on the environment e.g., solar, wind and tidal (Momoh *et al*., 2012). DGs are designed and installed mainly to supply a single end user's energy needs (i.e., stand-alone operation). In places where there is poor reliability and power quality, such as Nigeria, the DG will play a critical role; in which case DGs usually include traditional fossil fuel fired reciprocating engines or gas turbines (Ravindran and Victoire, 2018). Currently, the inadequate power supply in the Nigerian power sector has grown worse over a period of time due to increased power demand unmet occasioned by load growth, inability to install additional transmission lines, inability to build new large power generation stations to meet the power generation benchmark required to sustainably serve the growing population, as well as lack of technological development required to meet the present energy challenge (Abookazim *et al*., 2010; Momoh *et al*., 2012). Thus it is essential to integrate DG into the existing national grid so as to improve the system reliability, efficiency of power supply, voltage profile, power quality, and defer possible electric power infrastructure expansion (Shrivastava *et al*., 2012).

The benefits of integrating DG into the grid will be maximised if the siting of the DGs is optimal (i.e., placed on the best possible buses in the grid). Poor placement of DGs may increase power losses in the system since DG benefits are site and size specific, increase capital cost and operating cost, and poor power quality. It is necessary therefore to study the optimal location of DG in the power system network (Kumawat *et al*., 2015; Georgilakis *et al*., 2012; Shrivastava *et al*., 2012; Abookazim *et al*., 2010). The benefit of DG was classified into three main groups namely; technical advantages, economic benefits, and environmental advantages (Abookazim *et al*., 2010; Indhumathy *et al*., 2016). Thus, the technical advantages include grid reinforcement, improved system efficiency, enhanced system reliability, reduced power loss, better voltage profile, improved power quality and better load factor. The economic benefits are reduced transmission and distribution cost of operation, deferring power system reinforcement and expansion investment program. Other economic advantages are decrease in the price of electricity, enhanced productivity, minimised fuel costs due to improved efficiency, reduced reserve requirements and its corresponding cost. Whereas, the environmental advantages are minimal emission of greenhouse gases, reduced sound pollution (Abookazim *et al*., 2010; Indhumathy *et al*., 2016).

DG is a promising solution to the various problems faced by the power system. Among various challenges faced during DG planning, the problem of finding the best strategic location of DGs in the power system network is the most essential. Singh *et al*. (2011) reported that if DGs are wrongly sited in the system, it will gravely influence the voltage profile, and increase the power loss in the system. Willis (2000) developed an analytical method known as 2/3 rule for the placement of DGs. The 2/3 rule was initially applied for the optimal placement of shunt capacitors on the distribution network. The work opined that DG of approximately 2/3 capacity of the incoming generation be installed at approximately 2/3 of the length of the line. Zhu *et al*. (2006) observed that optimal placement of DG on network with time-varying load pattern will lead to a different optimal solution from placement of DGs for a static load condition. Using exhaustive search approach, a single DG installation is simulated with the objectives that reliability is maximized and power losses be minimized.

Wang and Nehrir (2004) developed an analytical method which uses bus admittance matrix (Ybus) method, generation information, and load distribution method for optimal placement of DG sources in power system with power loss minimization as the objective. The methods were tested on IEEE 6-bus and IEEE 30-bus test systems using time-varying and time invariant loads. The non-iterative nature of the methods eliminated convergence problem and produced faster solution. Series of simulation using PowerWorld simulation showed that the method can help designers in choosing proper site for DG placement. Borges and Falcao (2003) developed a methodology that implemented power summation method of load flow to evaluate the voltage profile and power losses with each DG unit represented as a PV bus with its voltage magnitudes specified. The conventional Newton-Raphson (N-R) and Fast-Decoupled methods of load flow were seen to be deficient for a radial network topology due to high R/X characteristics of cables, and unbalanced load operation.

Acharya *et al*. (2006) presented an analytical approach for the evaluation of the optimal size of DG. Their approach also establishes the optimal location of DGs for total power loss minimization. The developed method was implemented on IEEE 30-bus, 33-bus and 69-bus test systems to show its applicability on different network configurations. The obtained results from the methodology are compared with loss sensitivity method and exhaustive load flow methods. It is observed that loss sensitivity factor approach may not give the optimal placement of DGs for loss minimisation due to the linearisation of the originally non-linear exact loss formula. The shortcoming of Acharya *et al*. (2006) was resolved by the work of Kalambe *et al*. (2013) reported an analytical approach for the implementation of the two port transmission equation to allocate multiple DGs for loss minimisation. The method is verified on IEEE 33-bus test system and the result is compared with what was achieved with two different methods for loss minimisation - Exact loss formula and Exhaustive load flow methods. The stability of the test system is examined after DG installation using stability index. The stability index clearly shows the number of DG to be allocated in order to maintain stability of the system at the required level.

Gozel and Hocaoglu (2009) studied an analytical method which defined the proper size and location of DG. The method minimises the total power loss without the use of impedance matrix or the Jacobian matrix, but uses loss sensitivity factor based on equivalent current injection method. The approach is tested on IEEE-12 bus, 34 bus and 69 bus test systems. It is observed to be in agreement with other classical approaches but has faster computational time than other classical approaches. Singh and Parida (2010) investigated a method for the optimal placement of DGs using mixed integer non-linear programming in deregulated electricity market. This method is based on three objective functions; maximization of loading, minimization of real power loss, and minimization of cost of DGs. The three objective functions are formulated using three different optimal power flows (OPF) with different constraints. The technique has been tested on a standard 5 bus test system and on IEEE-24 bus reliability test system using MATLAB 7.8 with GAMS 23.2 solvers for solving the problem. The results showed that incorporation of DGs in both networks produced an almost uniformly distributed power flow in the network by alleviating overloaded lines and utilizing lines that initially were unutilized.

Keane and O'Malley (2005) developed a method which uses linear programming to optimally allocate DG on the distribution network for maximisation of generation capacity under technical constraints. The methodology is tested on a section of the Irish distribution network, and can be implemented on any distribution network across the world since they share the same structure/topology. The result achieved shows that capacity allocation of DGs on individual buses instead of on group of buses will cause network sterilization which will cause the bus involved to be constrained. Pesaran *et al.* (2014) assessed the use of weighted exhaustive search approach to determine the optimal location and sizing of single and multiple DGs for minimised active and reactive power loss and reduction of voltage deviation. The exhaustive search method incorporated the weight factor evaluation to change the multi-objective function into a single objective function with weights, and Newton-Raphson's (N-R) load flow method which evaluated the power loss of the test network. The method was implemented on IEEE-6 bus, 14 bus and 30 bus standard networks. The results showed that the weight factor did not affect the optimal position of DGs for 6 bus and 30 bus systems as it affected the 14 bus network.

Ishak *et al.* (2014) presents a method for identifying the optimal location and size of DGs based on the power stability index and particle swarm optimization (PSO) algorithm in which the model developed leads to better results compared to that obtained using only loss minimization approach. Dulaua *et al*. (2016) proffered solution to power losses by searching for the optimal location of distributed generator (DG) using IEEE 14 bus test system. Another extended this frontier by minimizing the system power loss via robustly detection of the optimal location and size of the distributed generators without violating the system constraints (Othman *et al.,* 2016). So also, Zongo and Andrew (2017) presented a solution to the problem of optimal allocation of distributed generator (DG) for multi objective minimization of four parameters through iterative search of each load bus until best minimum value of the objective function gave the best load bus for the DG installation. Biswas *et al*. (2017) developed a technique for simultaneously minimizing the real power loss and the net reactive power flow in the system when reinforced with distributed generators (DGs) and shunt capacitors (SCs). The resulted in better the system performance, higher reliability and elevated loading capacity which promoted increased in reduction of losses.

Heuristic Approach

Singh and Goswami (2009) presented a genetic algorithm (GA) based approach for optimal placement and sizing of DGs in power systems for voltage sensitive loads. The objective of this approach is to minimise the average locational charges for active power at buses. The locational charge has been modeled as a product of marginal loss coefficient and the per unit (p.u) cost for active power at reference bus subject to voltage constraint at each bus. The GA methodology was applied on a 13-bus radial distribution network and on IEEE 6-bus networked system for single DG placement and multiple DG placements. From the results obtained, it is observed that whereas DG size for both networks is affected by load models, the location of DG is almost fixed. Also, it is noticeably advantageous to place small capacity multiple DGs rather than a single large DG on each of the network without considering the variation in load modes. The method can be extended to the placement of any number of DGs on the network.

Khosravi (2014) applied GA to optimally place DG to minimise losses and voltage sag in radial distribution networks. This method combined load flow algorithm and three phase short circuit analysis with GA to obtain the optimal set of points. The method was implemented on 11 kV, 33-bus redial distribution network. The result showed that the number of DGs installed affected the power loss and voltage sag performance of the network. This method was applied on the assumption that considered only three phase faults and fault locations at the system buses only. Akorede *et al*. (2011) employed fuzzy GA method on a meshed network to achieve optimal allocation of DG units for the maximization of loading margin and profit. The two objective functions were combined to form a fuzzy multi-objective function with weighting factor using a fuzzy expert system. The fuzzificaton of the objective functions is to ensure better convergence than simplified GA approach. This methodology was implemented on the IEEE 6-bus and 30-bus test systems with the DGs connected for parallel operation mode. The result obtained showed that optimal sizing and siting of DGs is important in order to explore the benefits of DGs in the power system.

A GA based solution approach, with regard to the optimal sizing of DGs on radial distribution system was studied by Shukla *et al*. (2010). The objective of the approach was to minimize real power loss which translated to reduced energy loss cost and improved savings. Loss sensitivity analysis was integrated into the method through load flow analysis to determine the various buses for DG integration. Using the successive loss sensitivity analysis, multiple DGs were installed in the test networks used. The method was validated on the IEEE 33-bus and 69-bus test systems under three different modes of load conditions. The result showed that real power loss and real power loss cost decreased as the number of DGs increased up to a certain number above which it was no more economical to add more DGs. Apparao and Bhashna (2013) presented a Newton-Raphson's (N-R) load flow based approach using Particle Swarm Optimization (PSO) to optimally site DGs with the aim of minimising real power loss as well as the voltage profile improvement. This fast, simple but powerful intelligence search technique was implemented on the IEEE 33-bus Radial Distribution System (RDS). The results obtained showed the effectiveness of the method in optimally siting DGs for minimising real power loss and improving the voltage profile of the RDS.

Alhajri *et al*. (2007) developed the hybrid PSO methodology for power loss minimisation for optimal sizing and siting of DGs. The method is a combination of load flow algorithm and PSO which evaluated the optimal solutions. This method was tested on IEEE 69-bus distribution system. The results displayed an improvement in the voltage profile, phase angle deviation of the system as well as power loss reduction. Dharageshwari and Nayanatara (2015) applied simulated annealing as a solution method for optimal placement of DGs on IEEE 33-bus distribution network. This multi-objective approach employed the forward-backward sweep method of load flow analysis to evaluate the bus voltages and power loss of the distribution network. The methodology was tested on IEEE 33-bus test system for multi DG installation. The results depicted voltage profile improvement as well as power loss minimisation in direct proportion to increasing number of DG penetration (i.e., from 1 DG to 5 DGs).

Nara *et al*. (2001) applied Tabu search algorithm for optimal siting of DG for minimisation of losses. The method was tested on two distribution network models which provide electricity service to commercial, industrial and residential loads. The result proved that the Tabu search algorithm can be implemented for power loss reduction through careful allocation of DG units. However, the method adopted some assumptions such as uniformly distributed constant current load, unity power factor for section loads among others, which limits the applicability of the methodology. Seker and Hocaoglu (2013) investigated the application of artificial bee colony algorithm for optimal siting and sizing of DGs for ensuring real power loss minimisation subject to various constraints. The forward-backward sweep capability of the Thukaram's power flow algorithm was deployed in modeling the objective function so as to evaluate the branch currents as well as the node voltages for the radial networks. The method was tested on IEEE 33-bus and 69-bus radial distribution system and on IEEE 229-bus real test system. The results of the method were compared with greed search approach, and both were found to be closely the same.

Kaur *et al*. (2014) combined OPF and improved harmony search for optimal sizing and siting of (both single and multiple) DG units. The test was on both the DGs supplying real power only and those supplying both real and reactive powers. The hybrid methodology was simulated for IEEE 33-bus distribution system and the result showed that it can be used for the placement of any number of DG units on the network. The results obtained for the hybrid technique was compared with those of improved analytical and PSO techniques. The result showed the superiority of the technique in reducing line losses with smaller DG capacities and improved voltage profile as the number of DG units increases.

METHODOLOGY

This study methodology combines N-R method of load flow and SPEA-2. The N-R method is applied to determine the voltage profile of buses and active power losses of the power system. The optimal locations of DGs on weak buses (poor voltage profiles) are determined SPEA-2. The optimisation model that is considered for this purpose is presented in section 3.1, while a brief discussion on SPEA-2 is contained in section 3.2. The notations used to presents the optimisation model is given as follow:

nl	Number of transmission lines
g_k	Conductance of the *kth* line
V_i	Voltage of the *ith* bus
v_j	Voltage of the *jth* bus
V_{ref}	Rated voltage of a network
V_p	Voltage profile
NB	Number of load buses
X	line reactance
P_s	Sending bus active power
Q_r	Receiving bus reactive power
V_s	Sending bus voltage
V_k,	Bus voltages
V_k^{min}	Bus voltage lower limit
V_k^{max}	Bus voltage upper limit
P_{DGk},	DG real power connected to bus *k*
Q_{DGk}	DG reactive power connected to bus *k*

$P_{load(k)}$	Real part of the load connected to bus *k*
$Q_{load(k)}$	Reactive part of the load connected to bus *k*

Mathematical Model

Optimal placement of DGs within the power network involves the evaluation and determination of the size, location and the number of DG units to be installed without violating the operating constraint. The equations that describe the optimization problem are as follows:

$$J_1 = P_L = \sum_{k=1}^{nl} g_k\left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right] \quad (1)$$

$$J_2 = V_p = \sum_{i=1}^{NB}\left(V_i - V_{ref}\right)^2 \quad (2)$$

$$J_3 = LQP = 4\left(\frac{X}{V_s^2}\right)\left(Q_r + \frac{P_s^2 X}{V_s^2}\right) \quad (3)$$

$$V_k^{min} \le V_k \le V_k^{max} \quad (4)$$

From equation (4); the operating standard is:

$$0.95 \le V_k \le 1.05 \quad (5)$$

$$0 \le P_{DGk} \le \sum_{k=1}^{n} P_{load(k)} \quad (6)$$

$$0 \le Q_{DGk} \le \sum_{k=1}^{n} Q_{load(k)} \quad (7)$$

$$P_{Gk} - P_{Dk} - V_k \sum_{q=1}^{nb} V_q\left[G_{kq}\cos(\delta_k - \delta_q) + B_{kq}\sin(\delta_k - \delta_q)\right] = 0 \quad (8)$$

$$Q_{Gk} - Q_{Dk} - V_k \sum_{q=1}^{nb} V_q\left[G_{kq}\sin(\delta_k - \delta_q) - B_{kq}\cos(\delta_k - \delta_q)\right] = 0 \quad (9)$$

Equation (1) represents the expression for the minimisation of the total real power loss in DGs. This expression provides the relevant information for the real power loss at each branch of the network with respect to the load flow analysis. The minimisation of the bus voltage deviation of each bus in the power system with respect to the rated voltage of the network is expressed as Equation (2). The expression for maximisation of voltage stability factor is given as Equation (3), while the boundary of the voltage is as expressed by Equation (4). For the purpose of this study, the numerical value of the voltage tolerance inequality constraint is as given in Equation (5). The DG capacity should vary between zero and the total load in the system; this is as presented in Equations (6) and (7) (Jain *et al.*, 2011), Real and reactive power equality constraints or power flow constraints are checked to ensure that there is a load flow solution as expressed in Equations (8) and (9), respectively.

SPEA-2

SPEA-2 was designed to overcome the shortcomings of SPEA with regard to its fitness assignment strategy, density estimation techniques, and archive truncation strategy. SPEA-2 incorporates a nearest neighbour density estimation technique in to its structure in order to allow a more precise guidance of the search process (Al-Hajri and Abido, 2011). The steps for SPEA-2 are given as follow:

Step 1: Initialisation

Generate an initial population P_f with N size and create an empty external set (archive) $\bar{P}_0$ with $\bar{N}$ size.

Step 2: Fitness assignment

Calculate the fitness values of individuals in the external Pareto set $\bar{P}_t$ and the population P_t as follows:

Assign strength value S(*i*) for each individual *i* in the external Pareto set $\bar{P}_t$ and the population P_t. S(*i*) represents the number of individuals *i* dominates.

On the basis of S values, the raw fitness R(i) of an individual *i* is calculated using Equation (10). The raw fitness (D_i) is determined by the strength of its denominators in both the archive and population. When the raw fitness value of an individual is equal to zero, it implies that such individual is a non-dominated individual using Equation (11).

$$R(i) = \sum_{j \in P_t + \bar{P}_t,\, j > i} S(j) \quad (10)$$

$$D(i) = \begin{cases} 0 & \text{Non-dominated individual} \\ S(i) & \text{Otherwise} \end{cases} \quad (11)$$

(i) Calculate and sort the distance of each individual with respect to other individuals in the external and population sets. After sorting the list in increasing order, the distance to the kth individual, thus k = $\sqrt{\bar{N} + N}$ is dominated as σ_i^k. Discrimination among the raw fitness values of the population is achieved based on their density. Finally, the fitness value of each individual is obtained by adding the raw fitness; thus density of each individual using Equation (14).

$$D(i) = \frac{1}{\sigma_i^k + 2} \quad (12)$$

$$k = \sqrt{N + \bar{N}} \quad (13)$$

$$F(i) = R(i) + D(i) \quad (14)$$

Step 3: External set updating

The following steps are used to update the external Pareto set Search the population for the non-dominated individuals and copy them to the external Pareto set Search the external Pareto set for the non-dominated individuals.

If the number of the individuals in the external set $(\bar{P}_{t+1}) < \bar{N}$ (already specified external Pareto set). Then, the best dominated individuals are copied into the new external set until $|\bar{P}_{t+1}| = \bar{N}$.

If the number of individuals in the external set is $(\bar{P}_{t+1}) > \bar{N}$. Then, an archive truncation technique is invoked which iteratively removes individuals from $(\bar{P}_{t+1})$ until $(\bar{P}_{t+1}) = \bar{N}$.

Step 4: Selection

Select two individuals at random from the updated external set $\bar{P}_{t+1}$ and compare their fitness. Update the mating pool using the fittest individuals.

Step 5

Crossover and Mutation: Perform blend crossover and mutation (random) operations according to their probabilities to generate the new population.

Step 6: Termination
Check for stopping criteria (i.e., convergence or maximum generation). If anyone is satisfied, then stop the algorithm from further evaluation, else go to Step 2.

The flow chart for this process is presented in Figure 1.

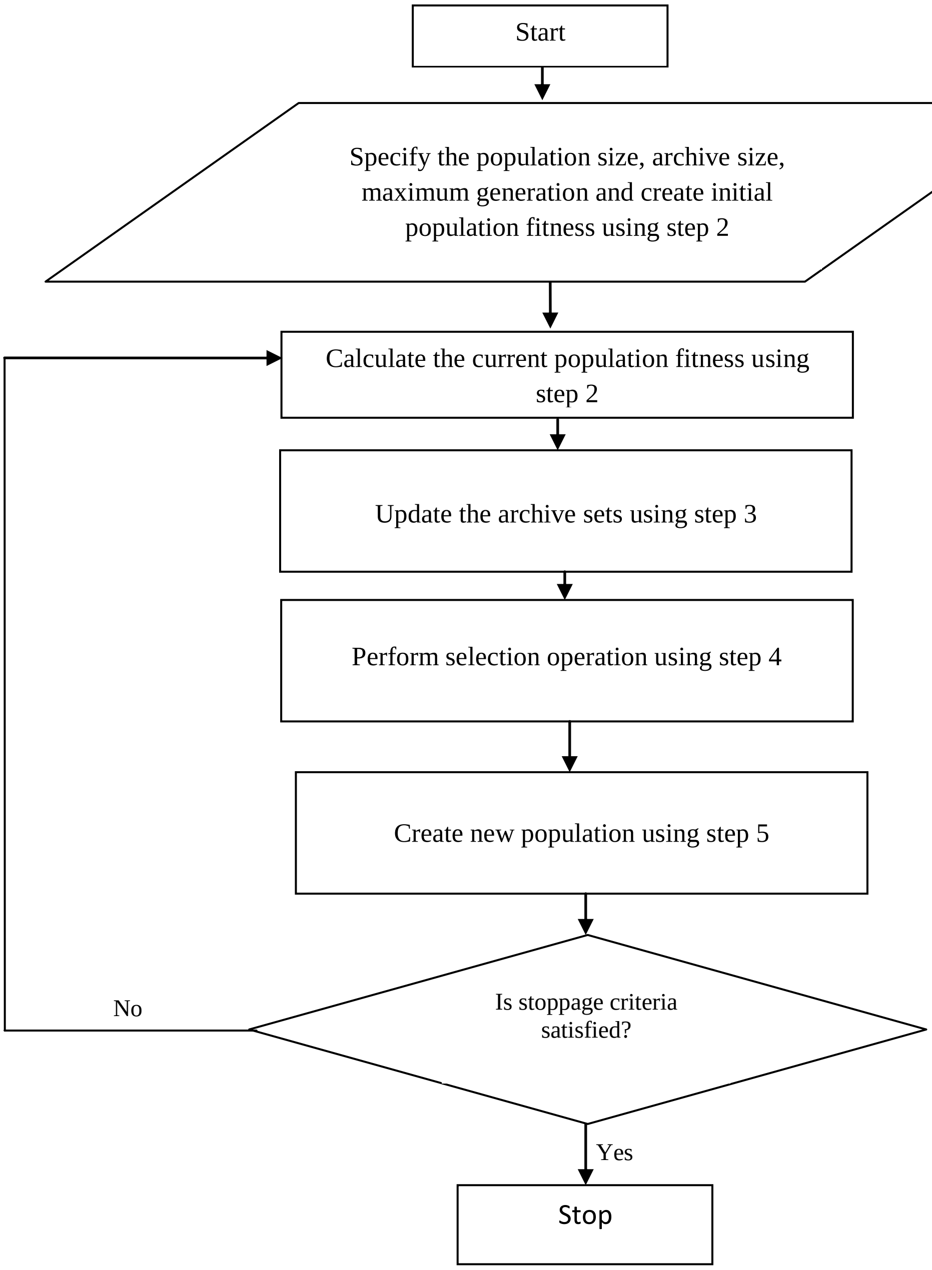

Figure 1: Flow chart for SPEA-2

Case Study
The applicability of this hybrid method will be authenticated using the IEEE 30-bus distribution system and the Nigeria-31, 330 kV, bus transmission network as contained in Figure 2. The data gathering method relied on collection of the bus and line data of the IEEE-30 network (from the e-laboratory of the Department of Electrical Engineering of the University of Washington) and the Nigeria-31 bus transmission data from the Transmission Company of Nigeria. The collected data was collated and analysis of the treated data. Based on the result of the data analysis, the following procedures were carried out namely: power flow analysis of the power system without DGs, deployment of the DGs on the buses identified with potential violation of network security using the SPEA-2, power flow analyses of the network with DGs installed and then investigation of the reliability of the hybrid system. The results of the analysis of the Nigeria-31 bus system are validated with the standard IEEE 30-bus test system (Reddy *et al.,* 2012).

Table 1: Parametric settings of the strength Pareto evolutionary algorithm (SPEA-2)

Parameter	**Values**
Population size	250
Archive size	50
Number of generations	100
Crossover probability	0.7
Mutation probability	0.3

The MATLAB software is used to write the script file for both N-R power flow solution and SPEA2 computations. The Pareto optimal frontier generated at the end of the optimisation run for the Nigerian network and that of the IEEE network are shown in Figures 3 and 4. In these figures the three parameters that were optimized were real power loss, voltage deviation and voltage stability. The optimization run times for the Nigeria-31 bus and the IEEE-30 bus networks are 2229.55 and 2039.42 seconds respectively. The simulation results of the Nigeria-31 bus network is thus validated with the IEEE 30-bus.

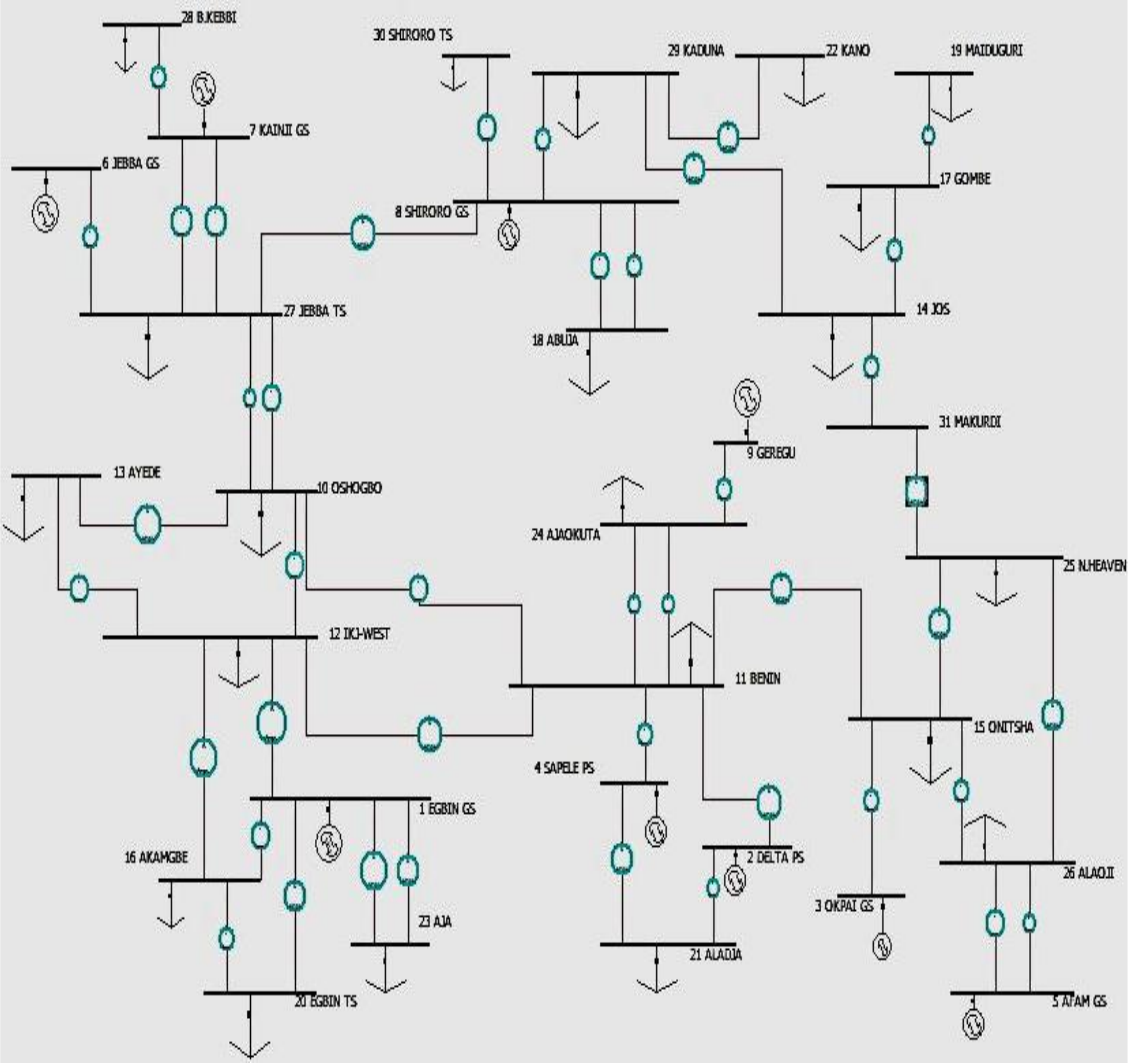

Figure 2: Single line diagram of Nigerian 31 bus transmission network

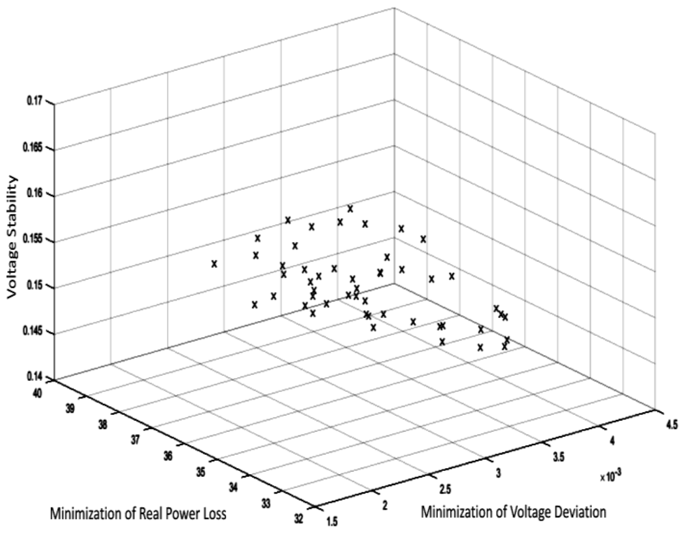

Figure 3: The Pareto optimal front for the Nigerian 31-bus system

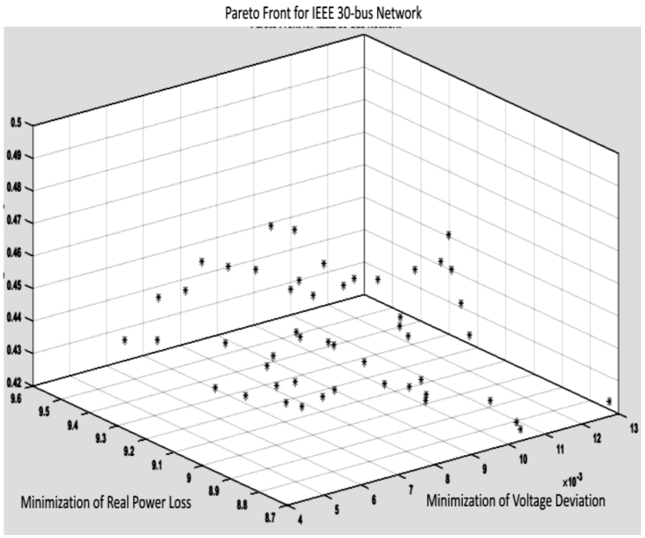

Figure 4: The Pareto optimal front for the IEEE 30-bus system

The last column of Table 2 depicts that the total power loss reduction in the system with respect to the no DG case, are in the tune of 7.78, 12.80 and 19.73% of real power for one DG, two DGs and three DGs, respectively; and 6.79, 11.18 and 18.52% of reactive power.

The optimisation result is shown in Table 3 with the optimal sizes and siting of DGs. The optimal buses as produced by the proposed method are 14, 15, and 17. The first optimal site is bus 17 which reduced the total line real power loss to 4.9% of its no DG value. Further decrease of 6.74 and 7.2% of the initial total line real power losses are observed after connecting two DGs and three DGs, respectively.

Table 2: The result of DG placement on IEEE 30 bus network

No. of DGs	Bus location of DGs	DG capacity (MW; MVar)	Total power loss (MW; MVar)	Percent power loss reduction (%)
No DG	-	-	17.528; 68.888	-
One DG	5	9.0148; 4.4052	16.165; 64.208	7.78; 6.79
Two DGs	5 7	8.1088; 4.9148 7.2723; 5.604	15.283; 61.187	12.80; 11.18
Three DGs	5 7 26	8.7793; 6.1272 8.1806; 4.7778 7.9567; 4.6281	14.070; 56.127	19.73; 18.52

Table 3: The result of DG placement on Nigeria 31 bus network

No. of DGs	Bus location of DGs	DG capacity (MW; MVar)	Total power loss (MW; MVar)	Percent power loss reduction (%)
No DG	-	-	36.445; 430.513	-
One DG	17	41.9475; 16.5437	34.660; 411.848	4.90; 4.34
Two DGs	15 17	35.3957; 15.2665 36.1442; 13.0485	33.990; 403.453	6.74; 6.29
Three DGs	14 15 17	22.9693; 15.2956 27.3711; 21.7274 30.9910; 15.4069	33.820; 400.544	7.20; 6.96

The results in Figure 5 were generated through Newton-Raphson's load flow studies carried out on the system. Figure 5shows the bus voltage is highest at bus 19 and lowest at bus 17 with voltages of 1.0530 and 0.9569 p.u, respectively (this is a violation of boundary condition in Equation (5)). The voltage distribution on all the buses shows that the voltage profile of the system can be improved to fall within the bus voltage permissible limit. Furthermore, Figure 6 shows the bus voltages vary from 0.9953p.u at bus 30 to 1.0820 p.u at bus 11. The aforelisted bus voltages are violating Equation (5), hence there is need for technical solution to this scenario. So also, it is observed that the voltages at buses 5, 7, 26, 29, and 30 are low compared to the other buses.

Figure 7 shows the voltage deviation of each bus voltage from the rated or reference voltage (Vref) of 1.00 p.u. This further shows that the voltage profile improvement can be achieved through the minimization of bus voltage deviation to fall as close as possible to zero. The voltage deviation of all the buses from the reference voltage of 1.0 p.u is plotted in Figure 8.

This figure (i.e. Figure 8) shows the absolute voltage deviation of each bus voltage from the reference value. For proper and reliable operation of the power system, the voltage deviation should be in the neighborhood of zero which means that the bus voltages should be very close to the rated bus voltage (i.e. 1.00 p.u).

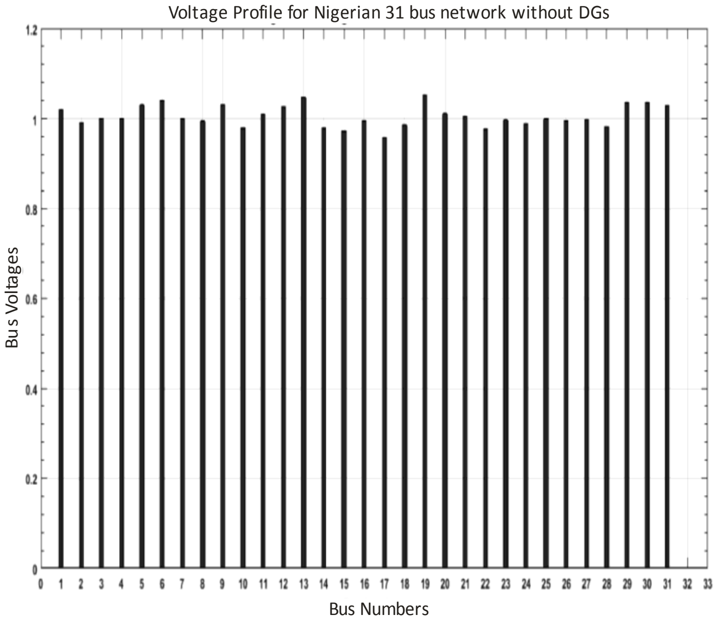

Figure 5: Voltage profile of Nigerian 31 bus network

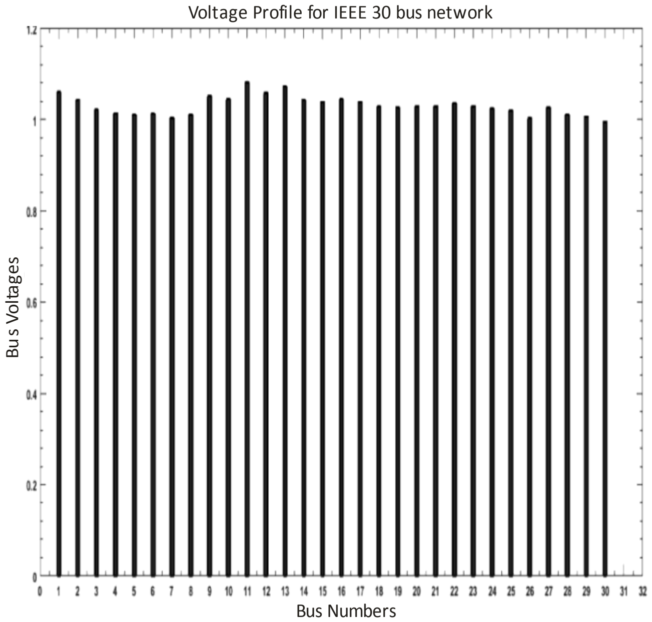

Figure 6: Voltage profile of the IEEE 30 bus network

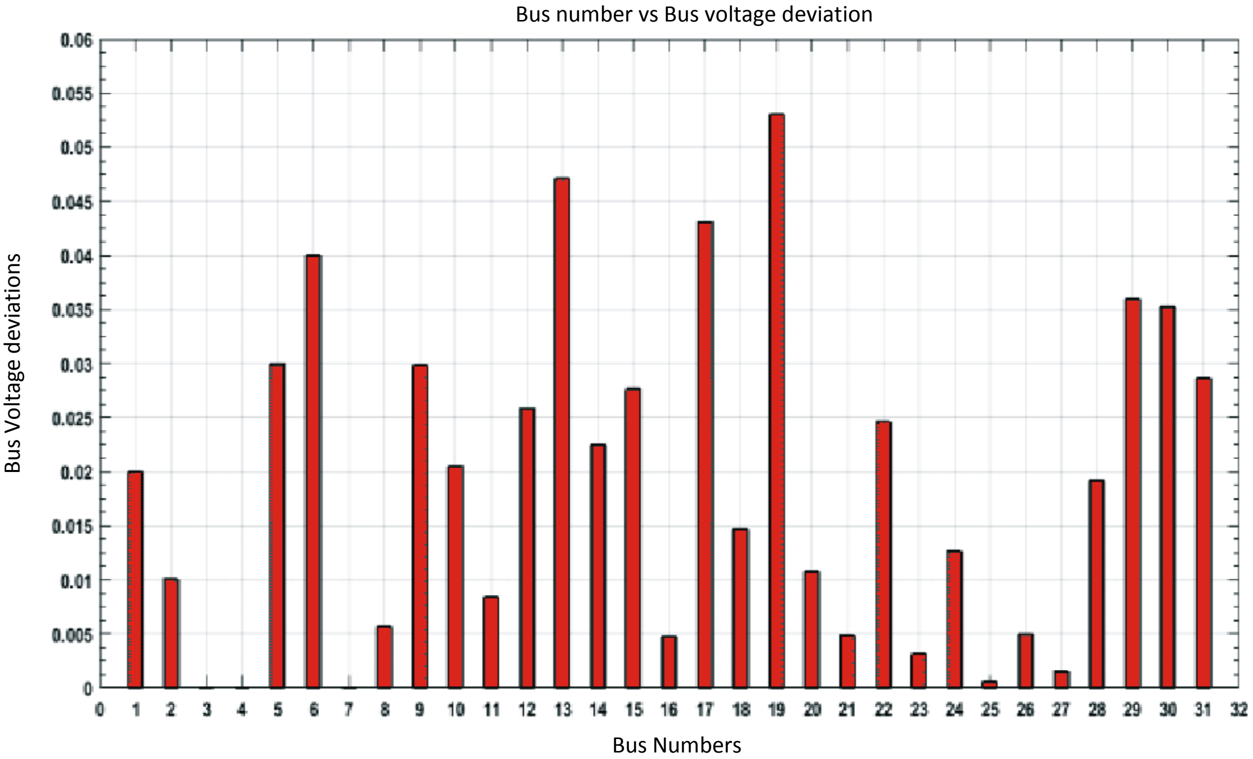

Figure 7: Voltage deviation of each bus for the Nigerian 31-bus network

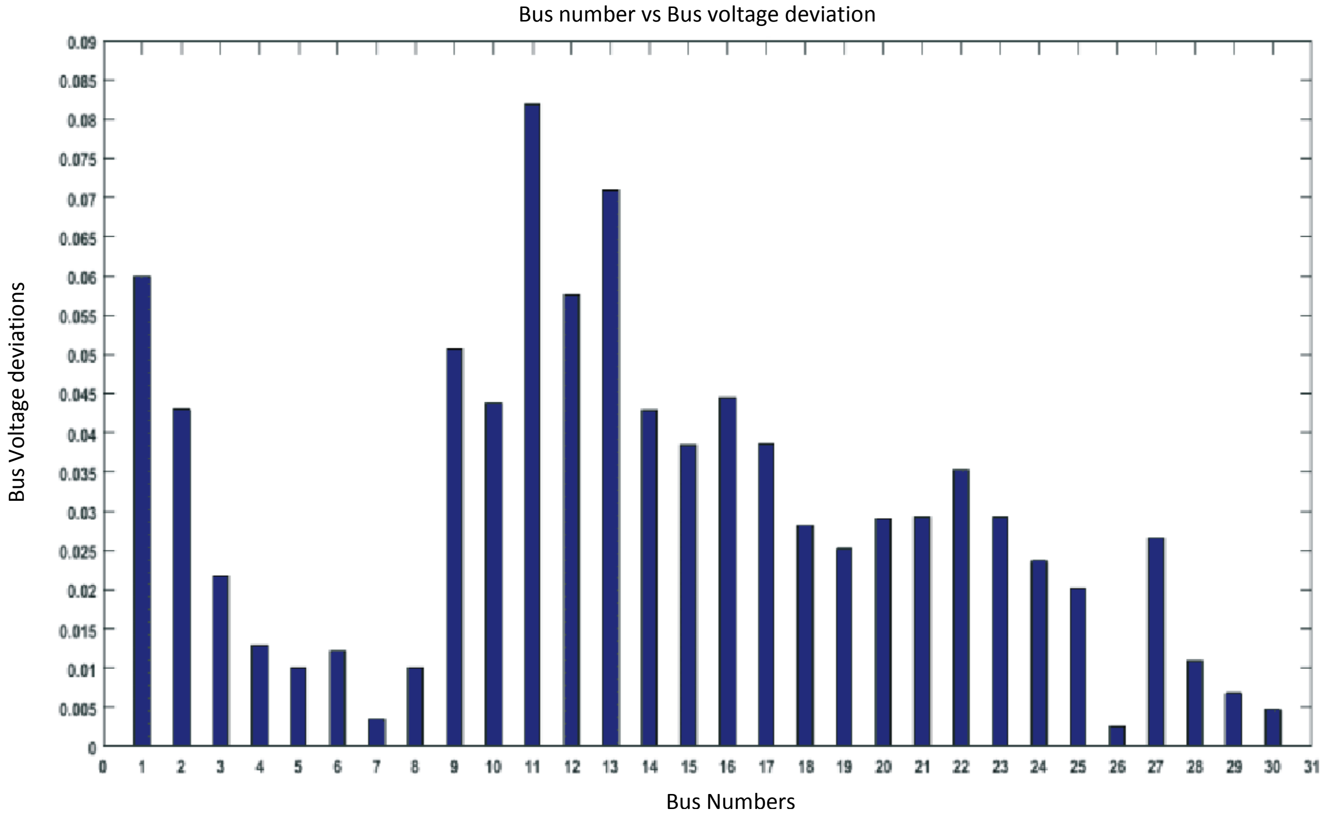

Figure 8: Voltage deviation of the IEEE 30-bus network

Figures 9 and 11 are the real and reactive power losses from all the branches of the Nigeria-31 bus network. These losses are 36.445 MW and 430.513 MVar respectively. While for the IEEE-30 bus network; the real and reactive power losses are shown in Figures 10 and 12. The total real and reactive power losses are 17.528 MW and 68.888 MVar respectively.

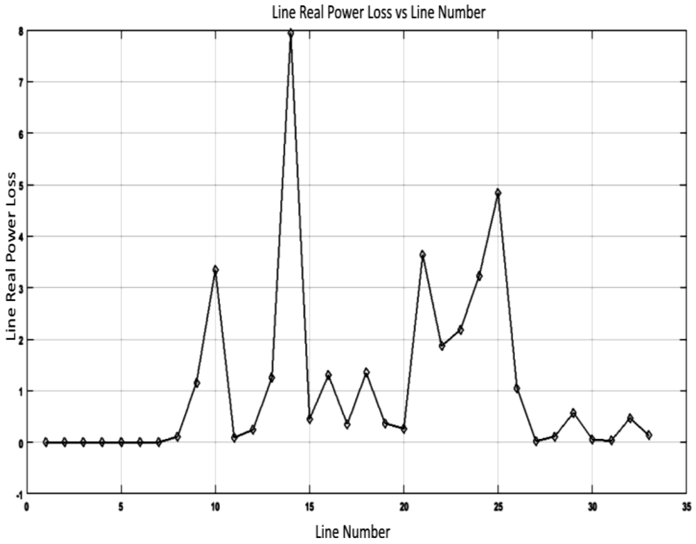

Figure 9: Real power loss for all branches for the Nigerian 31 bus without DGs

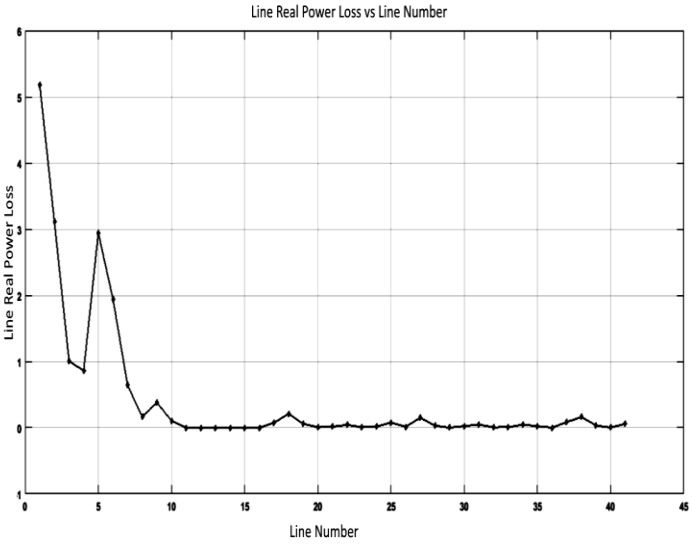

Figure 10: Real power loss for all branches for IEEE 30 bus without DGs

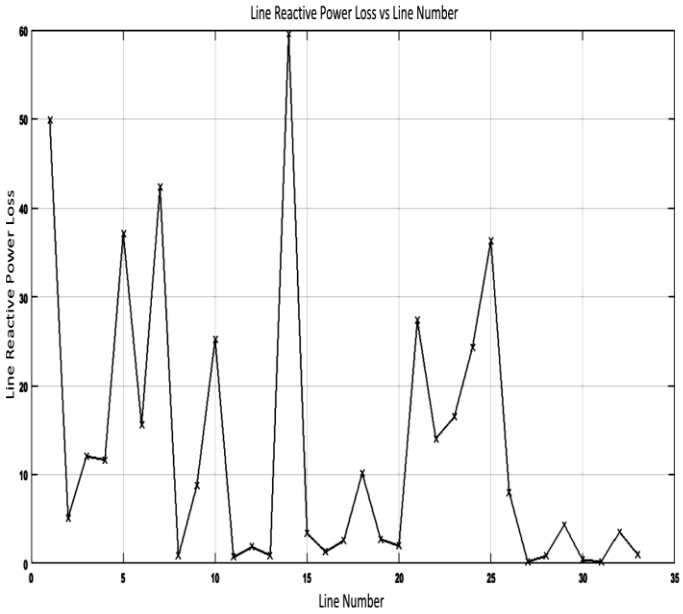

Figure 11: Reactive power loss for all branches for the Nigerian 31 bus without DGs

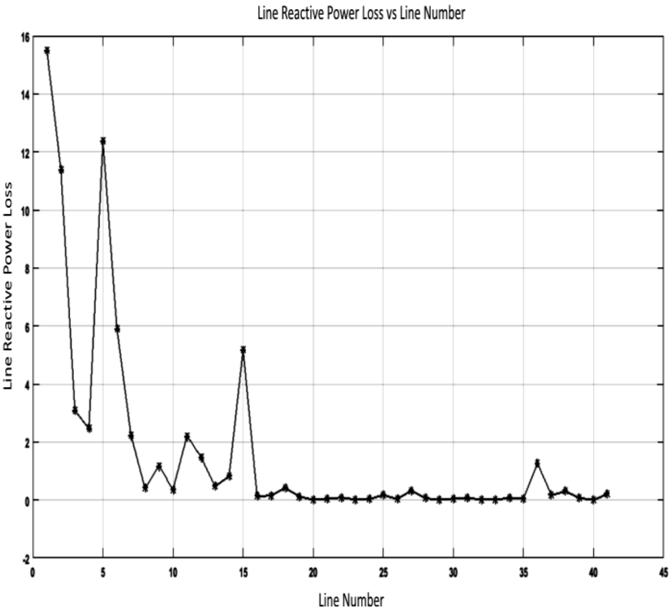

Figure 12: Reactive power loss for all branches for IEEE 30 bus without DGs

The real power losses for the Nigerian 31 buses show a constant value for the first seven buses as contained in Figure 13. However, an abnormal real power loss was observed at bus 14. The last two buses (i.e., 30 and 31) had zeros power losses (Figure 13). The real power losses for the IEEE 30 buses exhibit follows a steady decline for the first four buses after which a sharp increase in real power loss was observed at bus 5 (Figure 16). This trend was followed by another steady decline in real power losses (see buses 6 to 8). Figure 14 exhibits the remaining buses with an uneven steady increase and decrease in real power losses.

Figure 15 shows the tabular and bar chart comparisons of the per unit bus voltage profile of the system respectively. After connecting the first DG at bus 17, the bus voltage improved significantly from 0.9569 to 0.9728 p.u. Further improvement is experienced for two and three DG connections. The same effect is observed for buses 14 and 15 where DGs were sited. Figure 16 shows observed that the buses voltages improved within permissible limit as DGs are installed.

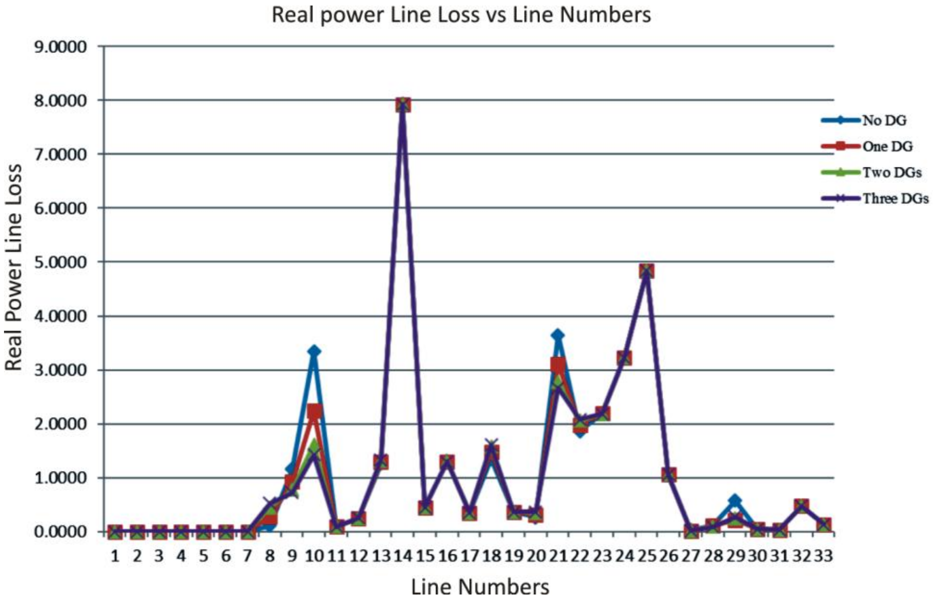

Figure 13: Real power losses for the various DG siting for Nigerian 31 bus

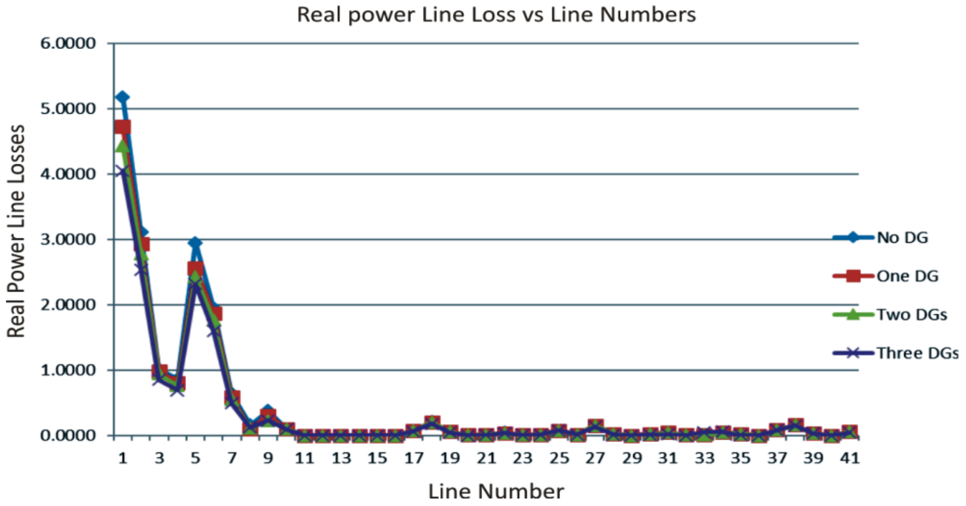

Figure 14: Real power losses for the various DG siting for IEEE 30 bus

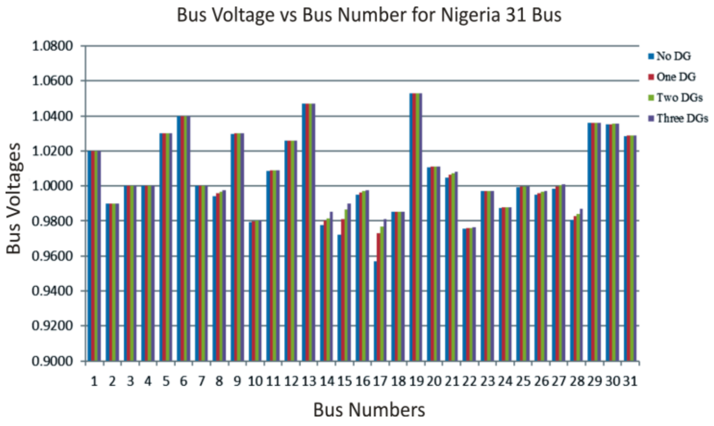

Figure 15: Voltages for the various numbers of DGs for IEEE 31 bus

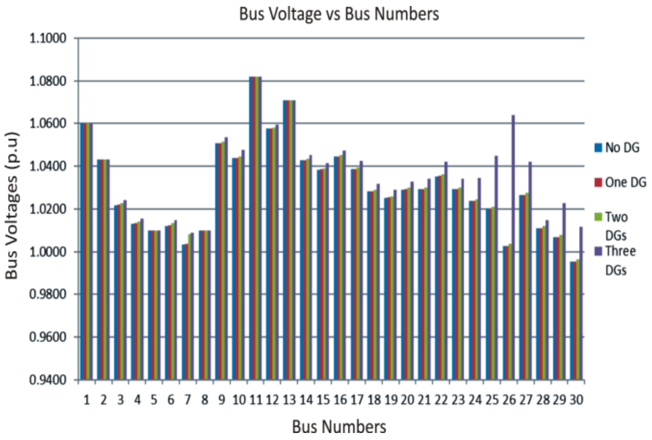

Figure 16: Voltages for the various numbers of DGs for IEEE 30 bus

CONCLUSIONS

In this study, the proposed solution method which incorporates the N-R load flow method and the SPEA2 is implemented using MATLAB. The proposed model was tested with the IEEE 30 and the Nigeria 31 bus networks by placing one, two and three each network. The total power losses for both test networks at no DG were compared with the values for one, two, and three DGs placements.

The Nigerian 31 and IEEE 30 bus total power loss reduction for the one placement were 1.363, 4.68 and 1.785 MW, 18.665 MVar, respectively. The Nigerian 31 and IEEE 30 bus total power loss reduction for the two placements were 2.245, 7.701 and 2.455 MW, 27.06 MVar, respectively. The Nigerian 31 and IEEE 30 bus total power loss reduction for the three placements were 2.625, 29.969 and 2.455 MW, 27.06 MVar, respectively. Based on these results, it can be concluded that the placement of DGs on Nigerian 31 and IEEE 30 bus reduce power loss significantly.

A further study which considered the application of other meta-heuristics such as differential evolution and PSO can be used to evaluate the performance of the SPEA-2.

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