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Reactive Power and Voltage Control of Nigerian Grid System Based on Artificial Bee Colony Algorithm

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***Abstract**: Reactive power and voltage control in electrical power system leads to simultaneous minimization of the real power losses and enhancement of voltage profiles at affected customers' buses. To achieve these goals available generating units' excitation systems, discrete tap positions of on-load tap changer of transformers are adjusted as well as switching of discrete doses of inductors and capacitors etc. at load buses. This is mixed integer non-linear optimization problem with the existence of multiple optimum solutions. Thus, there is a need to develop intelligent technology to achieve the global optimum solution. This paper presents the application of Artificial Bee Colony (ABC) Algorithm to solve the optimization problem using the above-mentioned control devices. The effectiveness of the developed algorithm has been demonstrated on standard IEEE 30 bus network and real 54-bus Nigeria 330kV grid system modelled in MATPOWER under three different loading scenarios. Simulation results on IEEE 30 bus revealed that the algorithm was able to achieve real power loss reduction of 0.9646%, 0.6384% and 6.01% while for 54-bus Nigeria 330kV grid system real power loss reduction of 9.497%, 7.45% and 10.12% was procured for 80%, 100% and 120% loading conditions respectively. For both system studies, the algorithm was able to eliminate the voltage limits violations. The approach was able to procure significant power loss reduction and eliminate the voltage limits violations by restoring them within limits. This thus leads to reduction in the cost of energy to the consumers and voltage profiles enhancement; hence improvement in the network power quality and voltage stability.*

***Keywords:** Reactive Power Optimization, Tap Changing under Load Transformers, Generating Unit Reactive Power, Artificial Bee Colony (ABC) Algorithm, MATLAB.*

1. INTRODUCTION

Due to steady increase in the complexity of electrical power system and the continuous high loading of network components, abnormal operating conditions such as under voltage may occur due largely to inadequate reactive power. Hence, the need for effective reactive power optimization (RPO) in a power system. Reactive power flow can be controlled by suitably adjusting the tap changing under load transformers (TCUL), generating unit reactive power capability and switching of discrete dose of capacitors and inductors. The foregoing control variables have their lower and upper permissible limits and are distributed system–wide. By changing a combination of these control variables discretely and/or continuously, manifest not only in adjusting the system voltage profiles to the desired limits but also the transmission losses are reduced.

Several numerical optimization techniques have been proposed within the framework of optimal power flow to assist the operator in reaching the optimal decision. Among these techniques are the Nonlinear Programming (NLP), successive linear programming, mixed integer programming, Newton and quadratic techniques have been proposed for solving the Var control problem [1]. These traditional techniques suffer from bad starting points and frequently converge to local minimum. In an attempt to circumvent the deficiencies of the conventional methods, several meta-heuristic techniques have been proposed with promising results [2].

In [3], DE and PSO were comparatively investigated on their ability to remove voltage limits violations and reduce power losses on the Nigerian grid system. Both algorithms were shown to be suitable in removing limit violations and PSO was shown to have a higher power loss reduction in some cases as compared to DE.

In [4], PSO algorithm was combined with an evolutionary concept to enhance its performance. A mutation operator was introduced into the PSO algorithm and results with the mutated PSO (MPSO) were compared against results with DE and a hybrid algorithm of PSO and DE, known as DEPSO on the Nigerian power system. The results were averaged over a large number runs to evaluate the effectiveness and the overall computational efficiency of the algorithms.

Differential evolutionary algorithm was proposed for optimal dispatch of reactive power and voltage control in power system [5]. The optimal setting of control variables such as generator voltages, tap positions of tap changing transformers and the number of shunt reactive compensation devices to be switched were determined. The algorithm was tested on standard IEEE 14, 30, 57 and 118-bus systems and the results compared with conventional method.

In [6], Gravitational Search Algorithm (GSA) for solving the optimal reactive power dispatch problem was proposed. The real power loss and voltage deviations were to be minimized individually. This algorithm has been applied on IEEE 30 bus system consisting six generators and compared other algorithms reported those before in literature. Results showed that GSA was more efficient than others for solution of single-objective ORPD problem.

In [7], Artificial Bee Colony algorithm for reactive power control and reduction of transmission loss was presented. The proposed algorithm was analysed and demonstrated on the standard IEEE 30-bus test system. Simulation results obtained revealed its robustness and effectiveness to solve the multi-objective RPO problem.

In [8], Differential Evolution (DE) algorithm for improvement in the voltage profile and simultaneously line loss reduction in power system was presented. With the help of DE, optimal setting of reactive power control variable were carried out. The proposed approach was tested on three standard IEEE system and obtained satisfactory simulation result.

In [9], Enriched Firefly Algorithm (EFA) was proposed to solve reactive power dispatch problem. A firefly algorithm (FA) is a population-based algorithm enthused by the social behaviour of fireflies. The proposed EFA extends the single population FA to the interacting multi-swarms by cooperative Models. The method has been evaluated on standard IEEE 30 bus test system. The simulation results showed that the proposed approach outperformed other reported algorithms in minimization of real power loss.

Comparative application of ant colony optimization (ACO) and BAT algorithm to find the optimal setting of on-load tap changing transformer (OLTC), generator excitation and static VAR compensator (SVC) to minimize the sum of square of the stability L-indices of all load buses was presented in [10]. Simulation studies revealed that both voltage profile and voltage stability was enhanced

In [11], ABC algorithm for solving optimal reactive power dispatch problem (ORPD). It was tested on the IEEE 30-bus and IEEE 118-bus systems and the results obtained were compared with those obtained using PSO, self–organizing hierarchical PSO–time varying acceleration coefficient (HPSO-TVAC), and other methods. It was concluded that the proposed method obtained better results.

Enriched firefly algorithm (EFA) to solve multi-objective optimal power dispatch problem simultaneously with load and wind generation uncertainties was proposed in [12]. The method was tested on IEEE30-bus test system. Simulation results showed that the proposed approach outperformed other reported algorithms in minimization of real power loss.

In [13], FA for reactive power control and power loss reduction was tested on IEEE 30–bus system was proposed. The results were compared to the biogeography based optimization (BBO) and particle swarm optimization (PSO). Test results showed that FA was more efficient and procured high quality solution.

` A new meta-heuristic Dragonfly Optimization Algorithm was proposed in [14] for solution of optimal reactive power dispatch problem. The proposed algorithm was tested on standard IEEE-14 bus and 30 bus systems. The dragonfly algorithm revealed the capability of increasing the antecedent optimization problem, focalized close to the global optimum.

Improved Bacterial Foraging Algorithm (IBFA) was demonstrated on a standard IEEE 33-bus RDS and a practical 50-bus Canteen feeder, Zaria, Nigeria [15]. The application of IBFA has not only improved the system parameters but shown a faster computation time when applied to two different systems.

Hybrid Bacteria Foraging Particle Swarm Optimization based optimal reactive power dispatch was proposed in [16] for the alleviation of voltage deviations. The proposed approach has been tested on standard IEEE 30 bus system and 24 bus EHV southern region equivalent Indian power system. The results obtained for multiple runs showed that the proposed hybrid algorithm not only giving better results compared to its basic counterparts but also returned more consistent results which are desirable for practical applications.

In this paper, the application of Artificial Bee Colony (ABC) algorithm for reactive power control in order to improve the voltage profile and minimize power loss is presented. The algorithm has been developed in the MATLAB environment using HP Pavilion 15t Intel Core i5, 1 Tb, 12 GB, 2 GB laptop. The effectiveness was demonstrated on two sample networks: standard IEEE 30-bus and practical 54-bus Nigerian 330kV grid system modeled in full operation detail in MATPOWER. Simulation results under three different loading scenarios on the above two networks for the algorithm as regard elimination of the voltage limit violations and active power loss reduction are presented.

2. PROBLEM FORMULATION

The reactive power and voltage control has a significant influence on security of the power system. For efficient and reliable operation of power systems, voltages at the terminal of all equipment in the system must be maintained within desired limits for power system stability enhancement. Proper redistribution of reactive power generations will offer the following benefits: Reduction in real power transmission losses caused by unnecessary reactive power flows which will consequently result in the lowest production cost; and Enhancement in system security from augmented reactive power reserves for emergencies.

The mathematical model for optimal reactive power and voltage control problem is formulated as follows [3]:

$$Min\ \ P_{T,loss}(X,U) = \sum_{j=1}^{nl} P_j \tag{1}$$

Subject to following constraints: $G(X,U) = 0 \quad H(X,U) \geq 0$

$$X^{\min} \leq X \leq X^{\max}$$

$$U^{\min} \leq U \leq U^{\max}$$

Where: P_j is the real power losses in line j; nl is the number of transmission lines.

$$X^T = \left[V_{L1}, V_{L2} \ldots, V_{L_{nd}}, Q_{g_1}, Q_{g_2} \ldots Q_{g_{ng}}\right]$$

$$U^T = \left[V_{g_1}, V_{g_2} \ldots V_{g_{ng}}, T_1, T_2 \ldots T_{nt}, Q_{C_1}, Q_{C_2} \ldots Q_{C_{nc}}\right]$$

X is the vector of dependent variables comprises of load bus voltages V_L, generator reactive power outputs Q_g. and U is the vector of control variables comprises of generator voltages V_g, transformer tap settings T, and shunt VAR compensation Q_C. G(X, U) = 0 and H(X, U) ≥0 are typical load flow equations. This is solved using the Newton Raphson power flow technique.

3. CONCEPT OF ARTIFICIAL BEE COLONY ALGORITHM

The artificial bee colony (ABC) algorithm is a novel heuristic algorithm inspired by the behavior of honeybee swarms searching for food sources, and the process of searching for an optimal solution simulates the behavior of honeybee swarms foraging for food sources with a maximum nectar amount. A food source foraged by honeybees represents a feasible solution of the optimization problem, and the i^{th} food source is given by eqn. (2):

$$X_i = (x_{i1}, x_{i2}, \ldots x_{iD}) \tag{2}$$

Where: D is the dimensions of the optimization problem.

The nectar amount of the food source represents the fitness value of the associated feasible solution. The honeybee swarms are divided into employed bees, onlooker bees and scout bees, and their numbers are N_e, N_o and N_c respectively. In the ABC optimization process, the employed bees do global search for new food sources and pass on the information about the nectar amount to the onlooker bees; the onlooker bees choose one employed bee by the roulette wheel selection and do local searching for a new food source around the chosen one; if a food source is not improved by a predetermined number limit of trials, then that food source will be abandoned by the employed bee, and the scout bee will randomly generate a new food source instead of the abandoned one, therefore, this step can effectively avoid local optima. The optimization process of the algorithm includes: initialization, employed bee phase, onlooker bee phase and scout bee phase as shown in Figure 1.

4. REALIZATION OF REACTIVE POWER DISPATCH VIA ABC ALGORITHM

The computational procedure adopted in the realization of ABC based approach for reactive power and voltage control is described as follows and shown in Figure 2:

Step 1: At the initialization stage, the relevant ABC parameters such as population size NP, maximum number of generation NG^{max}, search parameter space S_p and number of onlooker bees N_o, were defined. Also relevant power system data such as bus data, generator data and branch data required for power flow computation were actualized from the MATPOWER data files.

Step 2: Perform base case Newton Raphson (NR) power flow analysis in order to determine the initial bus voltage profile and active power losses respectively.

Step 3: With each reactive power control devices of generating units' set-points, transformer tap setting and switchable reactors treated as control variables, randomly generate initial population within the search space and compute the fitness function using varying fitness evaluation method [3] given by eqn. (3).

$$F_{fit} = (K + P_{Tloss}) \prod_{i=1}^{nb} d_i \tag{3}$$

Where; $$d_i = \begin{cases} 1 + z_i . V_{id} & if \quad V_{id} \succ V_{id}^{\max} or V_{id} \prec V_{id}^{\min} \\ 1 & otherwise \end{cases}$$

$$V_{id} = \begin{cases} V_{id} - V_{id}^{\max} & if \quad V_{id} \succ V_{id}^{\max} \\ V_{id}^{\min} - V_{id} & if \quad V_{id} \prec V_{id}^{\max} \end{cases}$$

P_{Tloss} is per unit power loss, the constant K is used to ensure that only non-negative values are assigned to the objective function. Constant z_i is used for the appropriate scaling of the constraint function values.

Step 4: Perform ABC algorithm operational phases: Employed bees, On-looker bees and Scout bee on the control parameters and compute the fitness function.
Step 5: Repeat step 4 until the convergence criterion of generation count greater than the pre-set maximum number of generations is met. The parameters of the fittest individual will be returned as the desired optimum settings.
Step 6: With the optimal setting of the control devices, perform final NR load flow analysis to obtain the final voltage profiles and the corresponding system power losses.

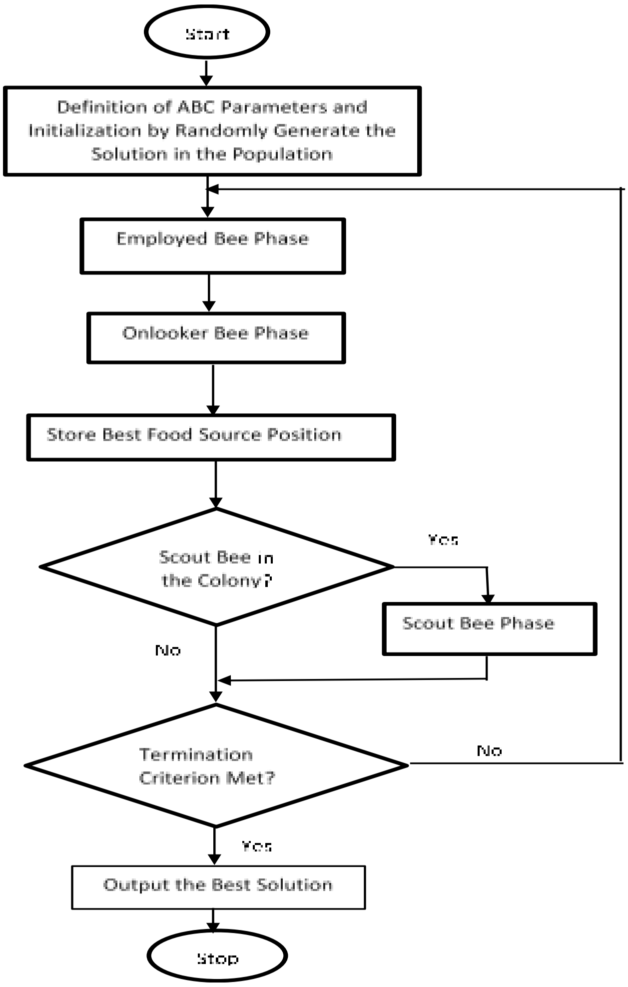

Figure 1: Flow Chart of Artificial Bee Colony Algorithm [18]

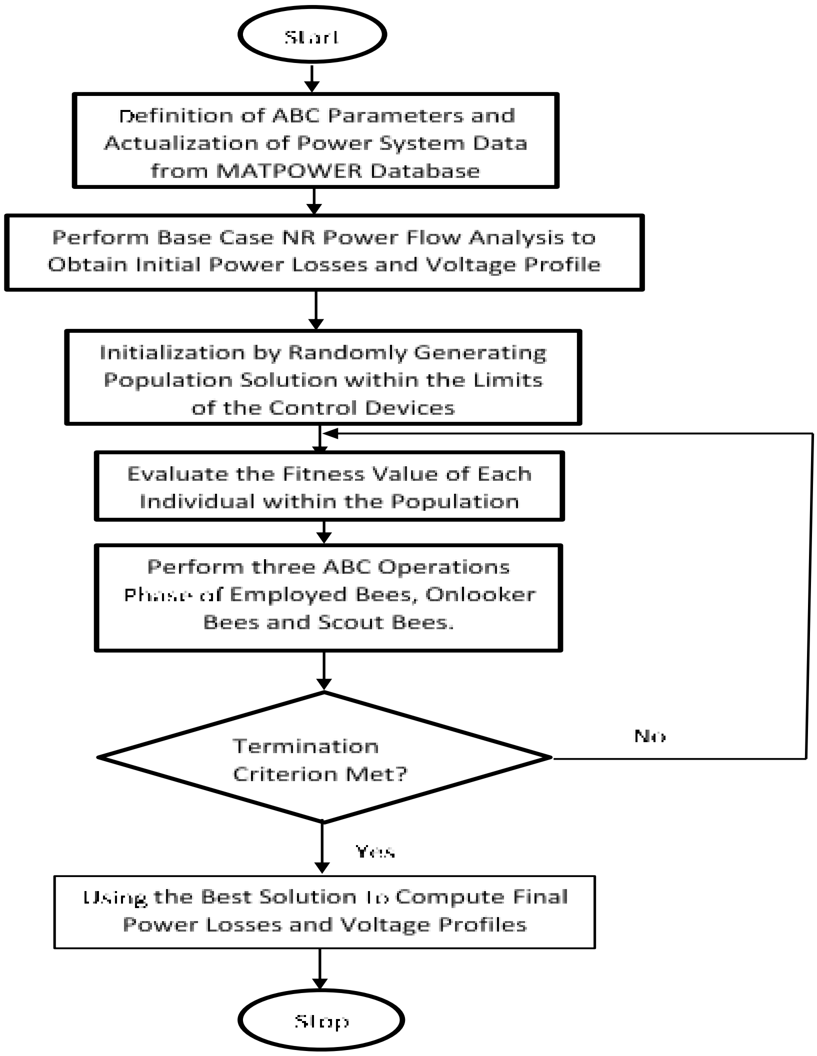

Figure 2: ABC based Reactive Power Optimization Implementation Flow Chart

5. SIMULATION STUDIES

To demonstrate the effectiveness of the developed ABC based reactive power optimization algorithm, it was tested on both standard IEEE 30 bus network and practical 54-bus Nigeria 330kV grid system.

5.1 Single Line Diagram and Network Data

The two power system networks considered for the purpose of verification of the developed algorithm are described as follows:

5.1.1 IEEE 30-bus test system

The system has 19- reactive power control variables are follows: 6- generator voltage magnitudes, 4 transformer tap settings and 9- switchable Var sources. The single line diagram of IEEE 30-bus test system and the data needed for modelling the network in MATPOWER for power flow analysis can be obtained from [17].

5.1.2 54-bus Nigerian 330kV grid system

The updated 54-bus Nigerian 330 kV grid network is characterized with major problems like voltage instability, long transmission lines, nature of transmission lines and high power losses which affect power generation and distribution systems. The updated Nigerian 330 kV grid consists of 54-buses, 12 generating stations and 36 transmission lines. The single line diagram of 330 kV Nigerian network is shown in Figure 3 and the data needed for modelling the network in MATPOWER for power flow analysis can be obtained from [17].

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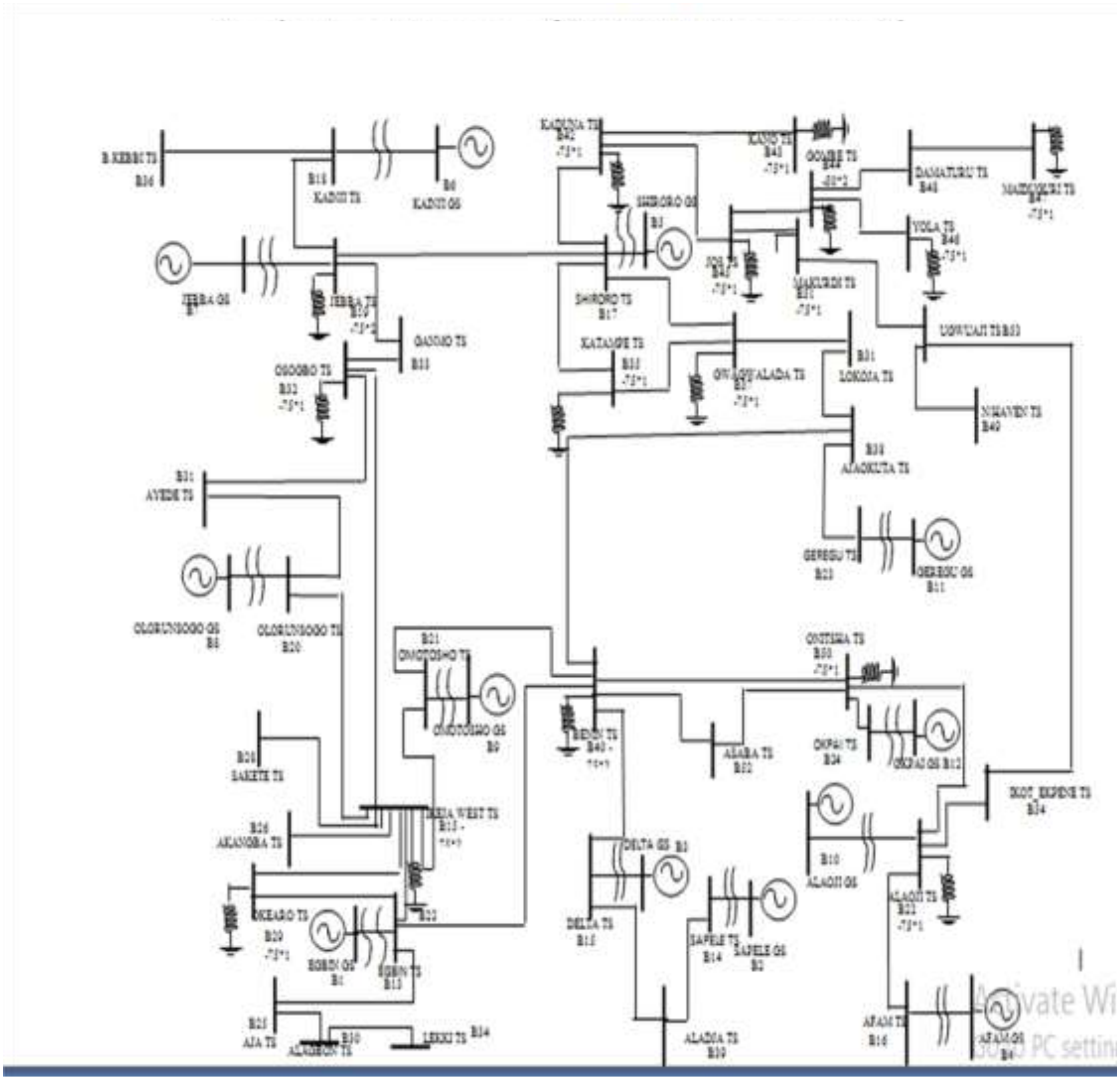

Figure 3: Single Line Diagram of Nigerian 330kV Grid System [17].

5.2 Simulation Studies on Standard 30 Bus IEEE System

A multitude of test cases were performed on the above named network using generating units excitation system, tap changing transformers and switchable Vars. Simulation results obtained for three different loading conditions: 80%, 100% and 120% are summarized in Table 1. Sample of voltage profile enhancement for 120% loading is shown in Figure 4 while Figure 5 shows the convergence characteristics of the ABC based RPO. The results obtained for the three case scenarios revealed that the approach was able to procure significant power loss reduction and eliminate the voltage limits violations by restoring them within limits. This thus leads to reduction in the cost of energy to the consumers and enhanced power quality and voltage stability.

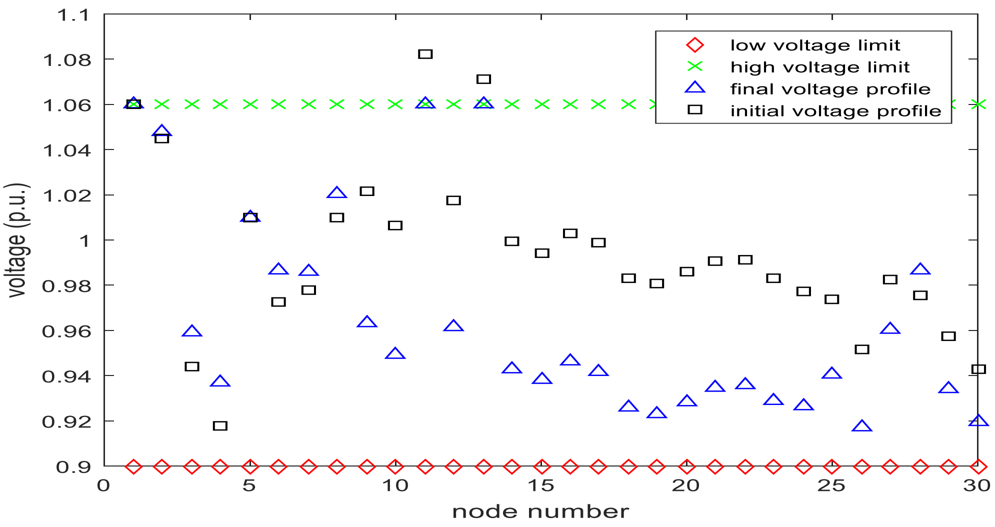

Figure 4: Voltage Profile Enhancement Using ABC based RPO for 120% Loading Condition.

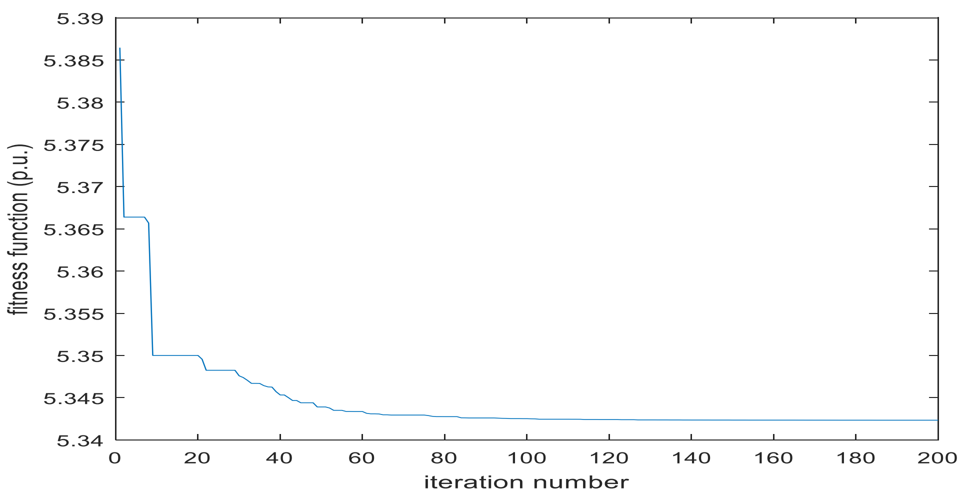

Figure 5: Convergence Characteristic of ABC based RPO for 120% Loading Condition

Table 1: Performance Indices for ABC based RPO using IEEE 30-Bus Study System

S/N	Parameter	80% Loading	100% Loading	120% Loading
1.	Initial Power Losses (MW)	10.6149	17.5569	36.4226
2.	Final Power Losses (MW)	10.5125	17.4449	34.2338
3.	Percentage Power Loss Reduction (%)	0.9646	0.6384	6.0096
4.	Number of buses violating the limits before ABC based RPO	3	2	2
5.	Number of buses violating the limits after ABC based RPO	0	0	0

5.3 Simulation Studies on 54-bus Nigerian 330kV Grid System

The developed algorithm was later applied to 54-bus Nigeria 330kV grid system considering three loading conditions; 80%, 100% and 120%. The developed algorithm of ABC based RPO was applied comprising 12 generating units, 13 tap changing transformers and 16 switchable reactors. The results obtained for the three case scenarios are summarized in Table 2 and the optimal parameter setting for ABC is shown in Table 3. Sample plots of voltage profile enhancement and convergence characteristics for 100% loading condition are shown in Figures 6 and 7. The percentage power loss reduction procured by application of ABC for RPO using Nigerian power system for the three loading conditions are 9.4973%, 7.4511% and 10.123% respectively while the voltage limits violation have been eliminated. The approach was able to procure significant power loss reduction and eliminate the voltage limits violations by restoring them within limits. This thus leads to reduction in the cost of energy to the consumers and voltage profiles enhancement; hence improvement in the network power quality and voltage stability.

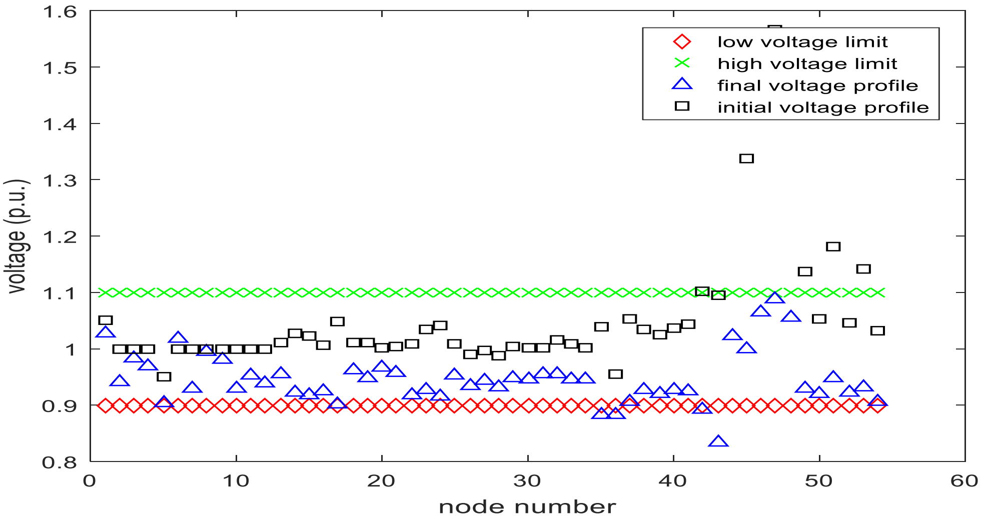

Figure 6: ABC based RPO Voltage Profile Enhancement and Loss Reduction for 100% Loading Condition for Nigerian 330kV Grid System

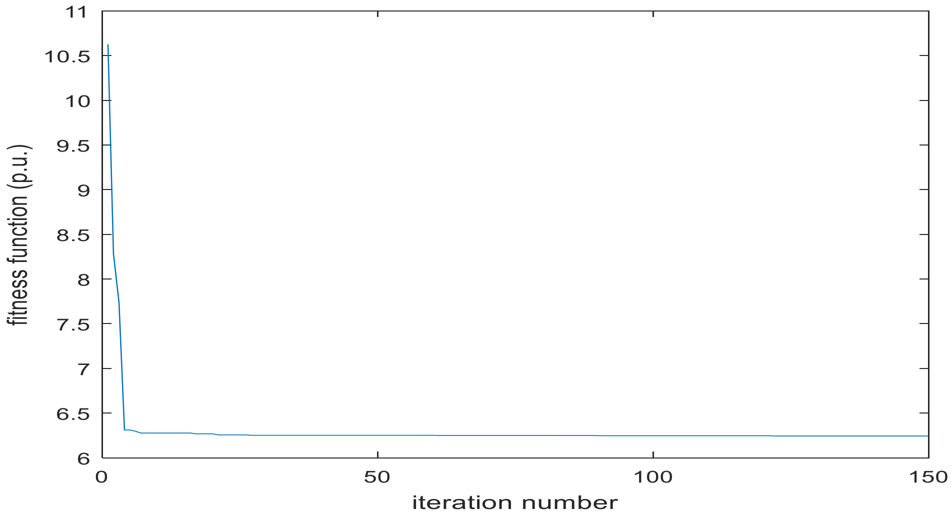

Figure 7: Convergence Characteristics for 100% Loading Condition for Nigerian 330kV System

Table 2: Performance Indices for ABC based RPO for Nigeria 330kV Grid System.

S/N	Parameter	80% Loading	100% Loading	120% Loading
1.	Initial Power Losses (MW)	163.8157	134.4376	158.9256
2.	Final Power Losses (MW)	148.2577	124.4205	142.8374
3.	Percentage Loss Reduction (%)	9.4973	7.4511	10.1231
4.	Number of buses violating the limits before ABC based RPO	4	4	3
5.	Number of buses violating the limits after ABC based RPO	1	1	0

Table 3: Optimal Parameter Setting for ABC based RPO for Nigeria 330kV Grid System

S/N	**Parameter**	**80% Loading**	**100% Loading**	**120% Loading**
1.	Maximum number of generation, NG^{max}	200	150	200
2.	Population size, NP	100	100	100
3.	Number of onlooker bees, N_o	100	100	100
4.	Search parameter space, D	41	41	41
5.	Fitness Constant, K	5	5	9

6. CONCLUSION

This paper presents the application of artificial bee colony for reactive power optimization of Nigerian 330kV grid system. The reactive power when optimally dispatch leads to improvement in voltage profile, reduction in transmission system real power loss and system voltage stability. Existing generator excitations, tap changing under load transformers and switchable reactors in the network were used as control devices. The developed algorithm has been successfully demonstrated on IEEE 30 bus system and real 54 bus-Nigerian 330kV grid system under three different loading scenarios. Simulation results revealed that the algorithm procured power loss reduction of 11.7208%, 7.4511% and 5.0158% for 80%, 100% and 120% loading conditions respectively with the consequent enhancement in system voltage profiles. This thus leads to reduction in the cost of energy to the consumers, improvement in the network power quality and voltage stability. For further work other meta-heuristic techniques such as firefly algorithm can be applied to this problem and the results compared. This will be thrust of our next research.

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