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A Survey of Optimal Power Flow Analysis of Longitudinal Power System

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Authors' contributions

This work was carried out in collaboration between all authors. Author AAG designed the study and wrote the protocol. Authors AOK and ABT wrote the first draft of the manuscript and managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

This paper presents a survey of publications on Optimal Power Flow (OPF) analysis of longitudinal power system with emphasis on the Nigerian power grid. It explained the nitty-gritty of OPF analysis. The study revealed that application of heuristic optimization techniques to OPF analysis have obviated the drawbacks of the previously used traditional optimization techniques with better solution quality, convergence time and flexibility. Although, the heuristics techniques were not flawless but well off to that of traditional techniques, a careful hybridization of both techniques seemed best off. This publication will be found handy for power system operators as well as researchers in an attempt to enhance the operations of the electrical power system.

Keywords: Longitudinal power system; Nigerian power system; optimal power flow; power system optimization.

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1. INTRODUCTION

Nowadays, electrical power is an indispensable product and continues to grow in importance due to its flexibility and other advantages over the other forms of energy. In a deregulated electricity of developing nations, with longitudinal structure of power grid. The continuous increase in power demand is fast outpacing the power system infrastructures, as such; operational problems and complexities become evident on such system. Technically, construction of a new power infrastructure is not only insufficient as a remedy of combating the menace but also militated against by problem right-of-way, environmental or socio-political issue, as well as energy resources management [1]. More so, construction of a new power infrastructure is rather a futuristic approach; cannot meet the present energy need. Enhancement or optimum utilization of the existing power system becomes a viable resort. However, the performance indices of the system in terms of security, reliability, stability and economical operation have to be in line with the enhancement. This is the concept of Optimal Power Flow (OPF), the subject of this article.

OPF is an optimization process applied to power system. It has been widely used in power system operations, analysis, scheduling, planning and energy management over the years and it is still becoming more relevant because of its several capabilities to deal with various situations of modern power system [2]. The optimization process is applicable to power system analysis based on the possibility of modeling power system parameters in terms of variables, constraints and objective function. In power system parlance, OPF is the process of obtaining the optimal setting of the control or decision variables within the electrical power network by optimizing (minimizing or maximizing) objective function of interest without violating the power flow constraints as well as the equipment operating limits while maintaining acceptable system performance in terms of generator capability limits, line flows and output of the compensating devices [3].

Like the conventional (non-optimal) power flow, OPF is also useful for real-time control, operational planning, scheduling, modern Energy Management Systems and also support deregulation transactions of electrical power system. Though the load flow is bereft of yielding the most economic, secure and optimum power system operation but in most cases, it serves as a precursor for OPF. While the economic dispatch; which is a particular case of OPF ignores or sometimes, partly up-keep the security of the system. But the OPF has the capability to determine the holistic optimal power system operation [1]. OPF also helps in determining the marginal cost data which in turn aids the pricing aspect of power system operation. It also furnishes the dispatchers or power system operators with possible tradeoffs between different objectives and also enlightens on which of the objectives will pay off, without violation of constraints.

A typical OPF problem is formulated in cognizance to the power network model, objective function, operating limits, and the intended solution technique. Due to its versatility, different formulations represent each of the possible cases of OPF and the quality of the result relies on accurate model formulation as well as the solution techniques. Among the OPF formulations are:

1. Optimal Scheduling: ensuring optimal generation with a saving (proper allocation) of the energy resources (fuel) invariably a saving in operating cost (fuel cost in thermal plants), such is a case of OPF called; classical economic dispatch [3].
2. Security - Constrained Optimal Power Flow (SCOPF): Curtailing outages and contingencies while ensuring optimum system operation. Also is the Security - Constrained Optimal Power Flow with Voltage Stability (SCOPF-VS) another particular case of OPF [4]
3. The scope of OPF can also be extended to accommodate Flexible Alternating Current Transmission System (FACTS) devices as well as renewable energy generation [1].

This paper is organized as follows: Section 2, discusses the longitudinal power system. Section 3, presents the methodology of OPF analysis. Section 4, presents the previous studies of OPF analysis on Nigerian power system and Section 5, presents the conclusion.

2. THE LONGITUDINAL POWER SYSTEM

Power systems with radial configurations and consisting of several long transmission lines are conventionally called Longitudinal Power System (LPS). Such power systems are commonly found in developing countries like Nigeria among

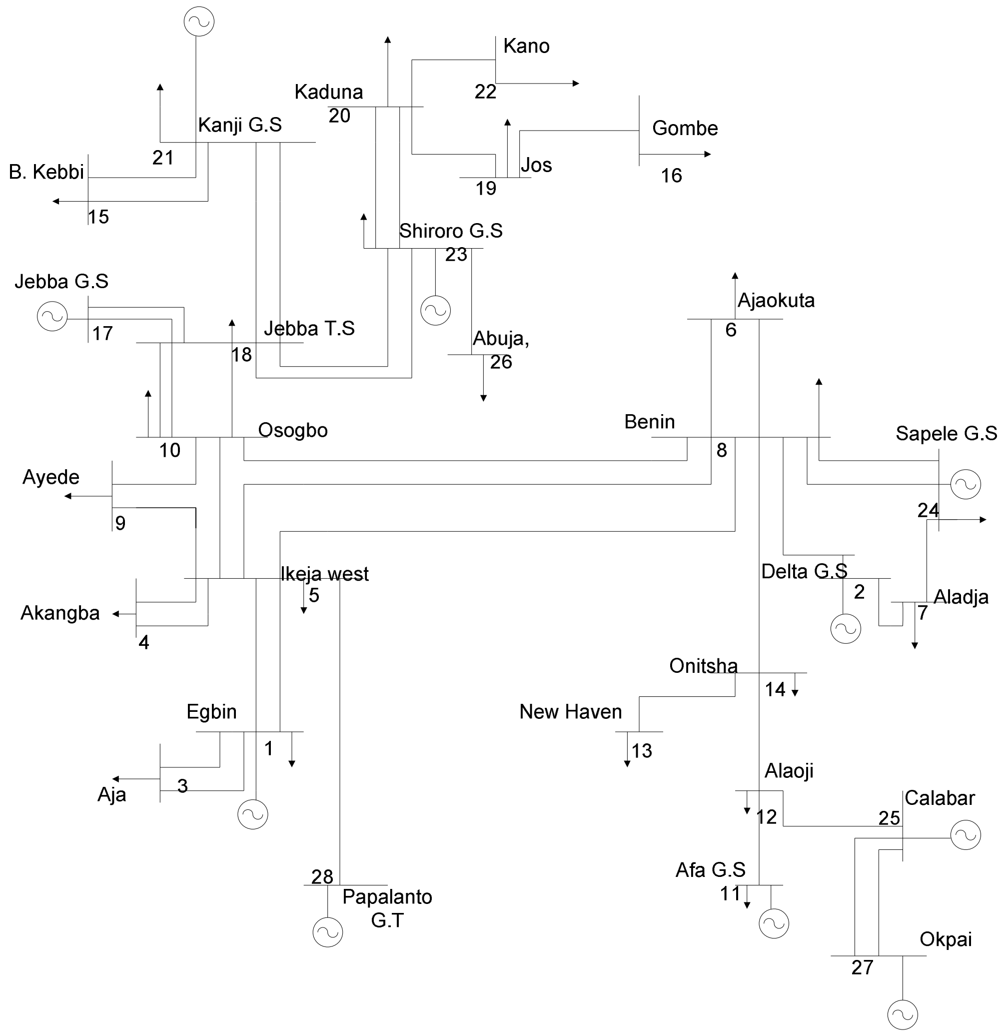

Fig. 1. Nigerian 330KV 28 Bus National Grid

others. The longitudinal power systems have inherent problems of voltage limit violations, high power losses and weak capacity for power transfer. Also, the generation centers of LPS are sparse and remote from load centers. LPS are very much sensitive to real and reactive power changes, low reliability, loadability limitation, stability problems, among others [5]. The single line diagram of 330kv 28bus Nigerian transmission network, with nine generating stations, 28 load stations and 44 transmission lines as described by [6], is as shown in above Fig. 1.

3. METHODOLOGY

The methodology of OPF is synonymous to that of a typical optimization process, with the appropriate problem formulation in terms of objective function, variables, and constraints such that it captures the desire of the system operators; then, the deployment of solution methodologies or optimization techniques to be used.

3.1 Optimal Power Flow Formulation

Several OPF formulations have been reported in the literature to address several instances of the problem. In recent times, the restructuring and developments in power system are causing increment in electric power system complexity. Also, the advent of Independent Power Producers and the prospect of integrating distributed and renewable generation in the grid, further expand the scope of OPF. Thus, various formulations abound, which goes by many names depending on choice of objective function and the constraints. Regardless of the name, any power systems optimization problem that includes a set of power flow equations in the constraints may be classified as a form of OPF [7].

In spite of the changes in the traditional power system operation and control due to increase in power system size and complexities, with the introduction of modern devices and renewable energy to alleviate the bottleneck and maximize system utility, the general structure of OPF formulation still maintains the classical format. Expressed as follows [7-9]:

$$\text{Optimize } F(x, u) \tag{1}$$

Subject to:

$$G(x, u) = 0 \tag{2}$$

$$H_{min}(x, u) \leq H(x, u) \leq H_{max}(x, u) \tag{3}$$

Where: (x,u) is the vector of controllable or independent variables and dependent or state variables of the system respectively; F(x,u), is the objective function: whose selection is based on the operating philosophy of the system operator; G(x,u) and H(x,u), are vector representing the system equality and inequality constraints respectively.

3.1.1 Variables of optimal power flow

OPF analysis requires certain power system variables to be controlled or modified in order to optimize the operation of electrical power system as well as variables to reflect the effect of the optimization processes. The variables are thus classified as the control (decision or independent) variables and the state or dependent variables. Generally, the state variables are said to be continuous in nature, while the control variables may be continuous or discrete; as in the case of switched devices or lines, where the variables are binary [10-12]. The examples of these variables were enumerated as follows:

The control variables include:

1. Active power at the generator buses except for the slack bus
2. Voltage magnitudes at the generator buses
3. Position of the transformer taps
4. Position of the phase shifter (quad booster) taps
5. Status of the switched capacitors and reactors
6. Control of power electronics (High Voltage Direct Current, FACTS)
7. Amount of load disconnected, etc.

While the state variables include:

1. Voltage magnitudes at load buses
2. Voltage phase angle at all buses
3. Active power output of the slack bus only.
4. Reactive power of all generator buses.
5. Line flows.

3.1.2 Constraints of optimal power flow

Constraints are generally regarded as an integral part of a practical optimization problem and are sometimes use as the key for the classification of OPF problems, for instance, the security-constrained OPF, economic dispatch, security-constrained with voltage stability. Besides, the system variables has to be within a permissible range (constrained), which should not be violated except causing damage to electrical power system equipment or resulting into a mal-operation. The constraints are generally categorized as equality and inequality constraints. More so, some of these constraints are easily handled except for the functional dependent ones of the inequality constraints, which employ the method of penalty functions, lagrange multiplier or others, in handling such functional constraints.

In OPF, the equality constraints are basically the power flow network equations, which can either be the steady state power flow or the contingency state power flow, either of which is non-linear though their level of complexity differs widely [12]. On the other hand, is the inequality constraints that specified the limits on the equipment of electrical power system as well as the limits needed to guarantee system security [13]. The inequality constraints are subdivided as follows as:

a) Control variables limits, which include:

- Generator real power

$$P_{G_i}^{min} \leq P_{G_i} \leq P_{G_i}^{max} \tag{4}$$

- Generator bus voltage

$$V_{G_i}^{min} \leq V_{G_i} \leq V_{G_i}^{max} \tag{5}$$

- Volt – Ampere Reactive (VAR) power

$$Q_{C_i}^{min} \leq Q_{Ci} \leq Q_{C_i}^{max} \quad (6)$$

- Transformer tap position

$$T_i^{min} \leq T_i \leq T_i^{max} \quad (7)$$

b) State variables limits :

- Voltage magnitude of load bus

$$V_{L_i}^{min} \leq V_{L_i} \leq V_{L_i}^{max} \quad (8)$$

- Line flow limits

$$S_{l_i} \leq S_{l_i}^{max} \quad (9)$$

Additional inequality constraints include reactive power of generator, prohibited zones of the generating units, rotor angle stability, limit on transient voltage electromagnetic field levels, etc [11].

3.1.3 Objective functions of optimal power flow

Practical OPF problems have several objective functions to reflect the different possible operations of power system; the objective function is multi-faceted as no single objective function fit into all the emerging scenarios of OPF. The selection and consideration of the objective functions depend on the operating philosophy of the power system operator [1]. The most commonly used objective function is the minimization of generation costs with and without consideration of system losses, since the issue of cost used to take precedence in power system operations. This is the classical case of OPF, called economic dispatch. Classical economic dispatch controls only the generation units to dispatch while OPF controls all power flow within the electrical power system [3].

It is to be noted that the cost, is the operating cost and not the total capital outlay of the power system, which is known in thermal and nuclear stations as the fuel cost. But for the case of hydro plants, where water seems free, there exist techniques for hydro scheme coordination as well as for incorporating pumped-storage hydro units into OPF formulation [14]. The fuel cost is usually equated to the operating cost or generating cost with the realization that other variables cost like: labour cost, maintenance cost, and fuel transportation cost, etc, which are difficult to express directly as a function of the output of the thermal generator unit, are expressed as a fixed portion of the fuel cost [3],[12]. Emphatically, fixed costs, such as the capital cost of installing equipment, are not included, only those costs that are a function of unit power output are considered in the OPF formulation.

Besides minimization of generation costs, other objectives functions are the minimization of system losses, maximization of voltage stability, maximization of power quality often through minimization from a given schedule of a control variable (such as voltage deviation) etc. Sometimes, in multi-objective problems, the objective functions are augmented with respect to one another, where importance is attached to a particular objective using the method of weighted sum, as seen in [13].

3.2 Optimization Techniques

The wide varieties of OPF formulations and the nature of the OPF problems, as previously discussed, brought about wide varieties of optimization techniques. In the past decades, OPF algorithms or techniques were designed in line with simplified assumptions of the problem formulation. Such techniques were termed as traditional or deterministic or better still mathematical optimization technique. These techniques have been applied to OPF problems and were used in power industry. However, these traditional techniques suffer some shortcomings, mainly as a result of the simplification made in the formulation of the problem, without which the technique might not converge; making the traditional technique has minimal applications [15].

However, the new dawns in optimization computations are the heuristics or non - deterministic optimization techniques, which differ conceptually from the traditional techniques, and are found to outweigh the shortcoming of the previously used traditional methods [15]. It is however noted that, there are still no known universal or almighty techniques that fits exactly for all varieties of the OPF problems, although some algorithms might perform excellently well than others in certain OPF model. A common theorem in this aspect of study is the no free lunch theorem; which states, no algorithms in all aspect is better than the other except in certain aspect where one may outweighs the others [16].

The heuristic techniques were however, reported with many theoretical advantages and practically outperform the classical techniques. Though, these heuristics techniques are computational intensive, are not inherently applicable to constrained problems and the development of their software package is burdensome relative to the traditional or deterministic techniques. Some of the performance metrics for discerning between the algorithms as used in OPF researches were identified by [17 - 18] as follows: computational speed, reliability, robustness, versatility or flexibility, scalability, solution quality and time of convergence. Evidently, it is very difficult for a single algorithm to possess all these traits. However, solution quality, robustness, time of convergence, reliability, and scalability should be considered in choosing and rating an OPF optimization technique [18].

3.2.1 Traditional or deterministic optimization techniques

These techniques are principally based on the criterion of local search for the optimal solution through the feasible region of the solution; these techniques use single path search methods and follow deterministic transition rules. These techniques are also known as derivative-based optimization methods, as its employed gradient and Hessian operators [7]. In these techniques, the criterion for optimality is based on Karush-Kuhn-Tucker (KKT) criterion which is a necessary but not sufficient criterion for optimality. These techniques have been widely used in solving optimization problems and OPF problems in particular, the reason being their efficiency, simplicity, solid mathematical foundation and readily available software tools for their implementation [2]. Common among these techniques as applied to OPF are: Newton method, simplex method, Lambda-iterative techniques, Gradient-based techniques, Linear and non-linear programming, Quadratic and dynamic programming and interior point method etc [15]. However, in spite of their application to OPF problem, the techniques suffer from the following drawbacks which make them to have minimal applications in solving practical OPF problems as reported in [15,2,7]:

- Local solvers; cannot guarantee global optimality except for the case of convex problem; because the KKT conditions are not sufficient for a global optimum.
- Uses approximate assumptions (such as linearity, differentiability, convexity etc.) which are unlike practical OPF problem.
- Sensitive to objective function and the initial estimate or starting points.
- The majority are meant to handle continuous variables, whereas the practical power systems consist of binary or integer and discrete variables.

3.2.2 Heuristic or non – deterministic optimization techniques

These techniques employed exhaustive or stochastic search with randomness in moving from one solution to the next in the feasible solution region to obtain the optimal solution, This majorly helps in circumventing being trapped in local minima. Thus, these techniques are versatile in handling various OPF format even with non-convexities and complicating constraints that are typical of practical OPF. These techniques are evolved to overcome the drawbacks of conventional techniques. Most of these techniques imitate certain natural phenomenon in their search for an optimal solution, which brought about their various categories [19].

Thus, each one of them has peculiar philosophy, but their common denominator is the systematic exploration of the search space for the solution. For instance, the philosophy of species evolution, is employed in the case of Genetic Algorithms (GA) and Evolutionary Programming (EP); the neural system philosophy, as the case of Artificial Neural Networks (ANN). The thermal annealing of heated solids as the case of Simulated Annealing (SA); and the philosophy of social behaviors and foraging of living things, as in the case of Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Fire-fly Algorithm, Teaching – Learning - Based Optimization(TLBO) and so on,[11]. These techniques are called many names, popular among are: heuristic, meta-heuristic, artificial intelligent, modern optimization technique etc.

It is to be emphasized that the application of these techniques requires selection of some algorithm specific parameters for their proper performance. Also, these techniques are inherently designed to handle unconstrained problems but with incorporation of penalty terms except when using the direct method, the constrained problems are easily handled. Most of these techniques are sensitive to the choice of parameter and penalty terms, such that the improper selections either increases the computational effort or yields the local optimal solution, also, a change in the parameters change their effectiveness [20]. The difficulty in the selection of algorithm parameters, and their lack of solid mathematical foundation with their complicated programming, are the major drawbacks of these techniques [11]. However, advancement in research is bringing to limelight some techniques that requires selection of fewer algorithm specific parameters, such techniques is the Teaching - Learning-Based Optimization (TLBO), Jaya algorithm among others [21].

3.2.3 Hybrid optimization techniques

Optimization techniques continue to grow in importance due to its wide range of application and thus become an active area of research. In spite of the landmark success of both deterministic and non-deterministic optimization techniques generally and in the aspect of OPF in particular, there are still some inherent shortcomings of each of these techniques. This brought about the quest of having hybrid optimization algorithm techniques that carefully combine two or more techniques into one, such that the advantages of each can be used to strengthen the others or to surmount its disadvantages. Significant improvements such as computation time, convergence properties, and solution quality or parameter robustness over each of the individual methods are achievable [19]. The hybridization could be:

i. Deterministic method combined : Instances of this as applicable to OPF are the Sequential Quadratic Programming (SQP) combined with quasi – Newton [20], Interior Point Method (IPMS) combined with Benders Decomposition [4], Interior Point Method (IPMS) combined with lagrangian Relaxation and Newton's method [22] etc.
ii. Deterministic and non-deterministic combined : Examples of this as applicable to various form of OPF are Newton's method combined with SA [23] , combined chaotic PSO with linear Interior Point Method (IPM) [24] Newton's method combined with PSO [25] etc.
iii. Non - deterministic Methods Combined: Differential Evolution (DE) combined with other meta-heuristics [26]; PSO combined with SA [27]; combined DE and SA [28], etc.

4. PREVIOUS STUDIES

Application of the variants of Genetic Algorithm (GA) to the problem of economic dispatch of generation was the focus of [29]. In the study, both the Conventional Genetic Algorithm (CGA) and Micro Genetic Algorithm (μGA) were applied to minimize the generation cost, the power balance constraints was the equality constraints considered. The authors reported that the major drawback of the CGA approach was that it could be time consuming. μGA approach was proposed as a better time efficient alternative. The effectiveness of both techniques to solving economic dispatch problem were initially verified on a 6-bus IEEE test system and then on the 31-bus Nigerian grid systems. It was concluded that the results obtained from both approaches were satisfactory. However, from the view point of economic and computational time, μGA performed better than the CGA and that of Newton-approach, on both the 6-bus IEEE test system and then on the 31-bus longitudinal Nigerian grid systems.

In [30], voltage profile correction and power loss minimization through reactive power control using DE and PSO technique were investigated. The feasibility, effectiveness and generic nature of both DE and PSO approaches were demonstrated on the 31- bus Nigerian grid system and the 39- bus New England power system with MATLAB application package. The simulation results revealed that both approaches were able to remove the voltage limit violations, but PSO procured in some instances slightly higher power loss reduction as compared with DE. However, DE was observed to require a considerably lower number of function evaluations while compared with PSO, if this observation could be substantiated by further investigation on the longitudinal Nigerian grid system, the DE approach will be more viable for potential real time application in control centre where the computation time is very relevant.

More so, the Elitist Non-dominated Sorting Genetic Algorithm II (NSGA-II), was applied to solve the multi-objective optimal dispatch of the Nigerian 24-bus hydrothermal power system with fuel cost and transmission loss as the objectives, with the consideration of power balance [31]. The authors established that the solutions obtained with NSGA-II converged better over both CGA and μGA approaches used in earlier studies on the Nigerian power grid. It was observed that as the modification of the algorithm increases, their performance get better.

The optimal dispatch of generation with the minimization of total generation cost and transmission losses of the Nigerian power system was examined in [32]. The Newton Raphson iterative technique for load flow analysis was modified to accommodate the models of optimal economic dispatch. The simulation was done with a MATLAB based program. At certain buses where voltage drops were noticed, Load Tap-changing Transformer (LTCT) were introduced to adjust the voltage magnitude, which furthered reduced the losses on the system. It was observed that the optimality in this study was determined based on KKT criterion; being a traditional technique, the result obtained trailed that of previous works [29-31], in solution quality and computation efficiency.

Constrained Elitist Genetic Algorithm (CEGA) was adopted in [33] to solve the economic load dispatch problem of the 31-bus Nigerian power system, to reduce both the transmission power loss and total cost of generation, while maintaining an acceptable generation output. Simulation results show that CEGA performed better while comparing with the result of the CGA and µGA, previously used with the same data set as reported in [29]. It was observed that the modification of the algorithm brought about a better result for the Nigerian power grid.

The optimal load dispatch in the South / South Zone of Nigeria Power System by means of a Particle Swarm optimization and Lambda-iteration techniques was investigated in [34]. The economic load dispatch problem were solved for two different cases, the Sapele plant with three units in generating stations and the Afam plant, with six units in the generating stations. The analysis was simulated on MATLAB software package. The objective was cost minimization with and without consideration of losses. It was reported that PSO gave a better solution in terms fuel cost and losses when compared to the result obtained by lambda-iteration, for the same test case.

The short-term economic load dispatch of Nigerian thermal power plants based on DE approach was the focused of [35]. The corresponding power loss and the total cost of production for each period were calculated. The work was in line with that of [29 and 30]. It was reported that the method is capable of being applied successfully to the economic dispatch problem of larger thermal power plants and can also be extended for longer durations. The authors' recommendation for future study was the use of load forecasting by means of artificial neural network to determine the load demand for a given period to be used for the economic load dispatch problem.

The study of [36] was different with the use of Power World Simulator and inclusion of Security (contingency) Constraint of Optimal Power Flow (SCOPF). Single line contingency cases were simulated. The results obtained show that the network was stable at pre-contingency state while a lot of violations occurred at the event of some single line contingencies. It was reported that to maintain security in the face of these credible contingencies, the network generators output were re-dispatched. Disparity and increase in bus marginal prices were observed; this was due to the cost of restoring security; as it comes with higher price unlike when there is no contingency. It is to be noted that contingencies are likely of a practical power system and the stability and reliability of the system are maintained with SCOPF but with a tradeoff of increased in bus marginal price.

The work of [37] reported the use of reactive power support (shunt capacitor compensation) to combat the problem of optimum cost of generation as well as loss minimization on the Nigerian power system. In the study, the inclusion of shunt capacitor to the inequality constraints, brought about a reduction in the total cost of generation as well as reduction in the total system losses with a significant improvement in the system voltage profile. The work was in line with that of [32] except with incorporation of shunt capacitor compensation in place of LTCT as a compensator.

Application of PSO to solving the Optimal Economic Load Dispatch of the Nigerian thermal system was the focused of [38]. The work was in line with the studies of [30], except that PSO technique minimizes the total production cost and transmission losses better and in some cases where the DE also performed equally well.

5. CONCLUSION

This paper has dissected and presented the nitty-gritty of Optimal Power Flow (OPF) analysis of a longitudinal power grid with emphasis on the

Nigerian power system. From the reviewed works, the heuristic or non – deterministic optimization techniques demonstrated its effectiveness and superiority over the traditional techniques with a better numerical result and computational time unlike the traditional techniques. Although, the programming aspect or the development of software package of the heuristics techniques might be tedious relative to traditional techniques. Noteworthy also, the performance of the non-deterministic techniques gets better as their modification and hybridization increases. These are cue for further works. Subsequent works should leverage on the application of non – deterministic and combinatorial (hybrid) optimization techniques to solving OPF problems. Also, effort should be taken in exploring other solution techniques like the Power System Analysis Toolbox (PSAT), Power World Simulator etc. and verify their viability in solving the optimal power flow problem of Nigerian power system.

More so, it was evident from the review that bulk of the studies focused on generation cost and transmission losses minimization; a particular case of OPF called economic dispatch. Extension of the scope of OPF to accommodate other operational constraints and objectives with the consideration of Flexible Alternating Current Transmission System (FACTS) controllers, hydro-plants, distributed generations, are also recommended; if included in the analysis, it will further enhance the performance and operation of the power system.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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