



Enhancement of Voltage Stability using Generalized Unified Power Flow Controller

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ABSTRACT

Increase in the demand of electrical power supply leads to heavy loading of transmission lines. As a result, there is insufficient reactive power availability which leads to voltage instability. To overcome the aforementioned problem leading to voltage instability and also to reduce the system losses, the use of FACTS devices arises. This paper is aimed at improving voltage stability on Nigeria 28-bus, 330kV transmission networks using Generalized Unified Power Flow Controller (GUPFC). A multi-objective optimization approach based on minimization of active power loss and voltage deviation to determine the optimal location and size of GUPFC using Particle Swarm Optimization (PSO) was developed. The simulation results demonstrated significant improvement of the PSO model with a 30.99% reduction in total active power loss and 2.49% improvement in the overall voltage profile.

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INTRODUCTION

Numerous interruption of electrical power system in Nigeria has almost become usual aspects that establish or create problems associated with loss of goods and services for consumers, and power service providers. Virtually all electricity consumers have expressed their concern over the deterioration of quality of electrical power supply in the country. Indeed, this condition has led to the rapid growth of standby electricity power supplies in large consumer locations and domestic residences (Nwohu, 2016). Similar to several transmission systems across the globe, the Nigerian transmission system has been characterized as, high technical and non-technical losses, voltage instability and over loading. These features result in obsolete substations and de-regularized electricity market (Elechi and Omoroguiwa, 2015).

Voltage stability has been the subject of concern over the last few decades, which saw a lot of research works conducted in the area of voltage stability. The significance of voltage stability phenomenon has been on the rise in planning and operation of the present day power systems (Kalaivani and Kamaraj, 2011). A disturbance, such as a line or power plant tripping, can initiate voltage instability and could lead to voltage collapse. "Voltage collapse is the process of which the sequence of events accompanying voltage instability leads to unacceptable voltage profile in a significant part of the power system" (Singh, 2011). A system enters a state of voltage instability when there is disturbance, increase in load demand or change in system condition causes gradual and voltage which can no longer be controlled. The main factor causing instability is the inability of the



power system to meet the demand of reactive power (Adebayo and Sun, 2017).

With the development of Flexible AC Transmission System (FACTS) devices, power system performance has improved. FACTS is a concept based on power-electronic controllers, which has the potential to improve the power transfer capacity of the line (Suchak, *et al.*, 2017). FACTS controllers have the capability to control power flow and improve stability of the system by controlling one or more transmission system parameters (e.g., voltage, line impedance, and phase angle) (Kumar and Kumar, 2011). Connections in FACTS are of different types. When FACTS controllers are connected in shunt, they provide voltage support at critical buses in the system and when connected in series, they regulate power flow in critical lines (Valencia, *et al.*, 2002). Voltage and power flow are controlled simultaneously by the combined series and shunt controllers (Lubis, 2011). Among the FACTS controllers, Generalized Unified Power Flow Controller (GUPFC) is one of the novel most flexible FACTS device; this device allows the controlling of power flow of multi lines or even sub-network, rather than controlling the power flow of a single line. GUPFC extend the concept of voltage and power flow control beyond what is achievable with the known two converter UPFC FACTS controller (Suresh and Raju, 2015). The simplest GUPFC consists of three converters, one connected in shunt and the other two are connected in series with the two transmission lines in a substation. GUPFC can control power system quantities such as voltage magnitude and independent active and reactive power flows of the two lines (Zhang, 2006). GUPFC can be used to increase the transfer capability of a transmission line significantly as well to relieve congestion in a flexible way. In order to analyze the effects of GUPFC in a power

system effectively, it is of paramount importance to develop GUPFC steady state models that is suitable for implementation of load flow (Santos, *et al.*, 2013).

The effectiveness of FACTS devices depends on optimal location and sizing in the network. In recent years, several meta-heuristics algorithms such as ant colony optimization (Fughur and Nwohu, 2014), genetic algorithm (Omorogiuwa and Onahaebi, 2015), bacteria foraging algorithm (Tripathy and Mishra, 2007), firefly algorithm (Selvarasu, *et al.*, 2013), biogeography algorithm (Subramanian and Ravi, 2012) have all been deployed for optimal placement of FACTS devices. As it appears, none of the works have employed a single technique in obtaining both the optimal size and location of FACTS devices in the networks, as all authors used separate technique in determining the optimal location.

Therefore, this paper employed a particle swarm optimization based technique for GUPFC optimal placement and sizing in Nigeria transmission network to enhance the voltage profiles, reduce the overall system losses.

The rest of the paper is organized as follows: Section 2 presents the GUPFC overview. Section 3 gives a general problem formulation. The concept of PSO is described in section 4. The materials and methods used are in section 5. Simulation results are discussed in section 6. Finally, conclusion is summarized in section 7.

GENERALIZED UNIFIED POWER FLOW CONTROLLER

By combining three or more converters in the GUPFC, it extends the concepts of voltage and power flow control beyond what is achievable with the known two-converter UPFC and IPFC FACTS controllers. The simplest GUPFC shown in figure 1 consists of three converters. One

converter is connected in shunt with a bus and the other two converters are connected in series with two transmission lines through a coupling transformer in a substation. Balancing of active power required by the series converters and also providing the shunt reactive compensation so as to regulate the voltage magnitude, is done by a shunt converter. While the provision of active and reactive power compensation so as to control the active and

reactive power of their series connected transmission is done by the series converters. In a steady state operation, the main objective of a GUPFC is to control the voltage and power flow (Santos, *et al.*, 2013).

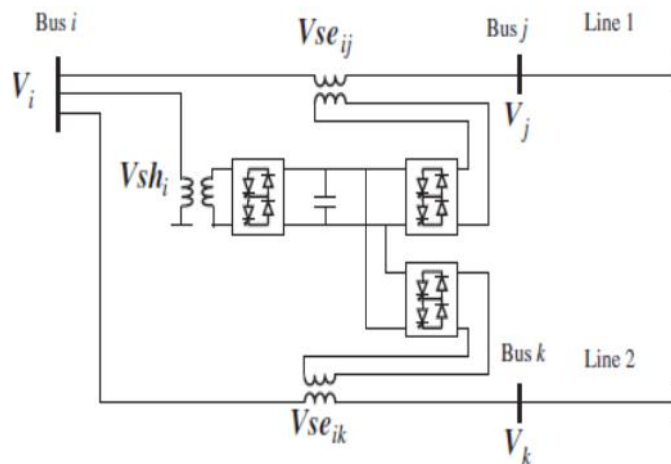


Figure 1: Typical GUPFC with three voltage source converter (Zhang, 2006).

PROBLEM FORMULATION

The idea of optimal placement and sizing of GUPFC in transmission networks is to minimize the network losses and improve the overall voltage profile. The motive here is to minimize active power loss P_T (loss) and voltage deviation VD expressed by:

The network overall active power loss function is given by:

$$P_L = \sum_{i=1}^{N_L} G_{i,j} [V_i^2 + V_j^2 - 2V_i V_j (\cos \delta_i - \delta_j)] \quad (1)$$

The voltage deviation function is expressed as:

$$VD = \sum_{i=1}^N (V_i - V_r)^2 \quad (2)$$

The multi-objective function (J) can be formulated mathematically using the

weighted sum of equations (1) and (2) to give:

$$\text{Minimize } (J) = m (\omega_1 P_L + \omega_2 VD) \quad (3)$$

Where ω_1 and ω_2 are the weighting factors used for adjusting the network total active power loss and voltage deviation functions respectively. A unit weighting metric is assigned to both objective functions due to the equal importance attached to both objectives.

The equality constraints comprises of the network power equations expressed as:

$$P_G - P_D - V_i \sum_{j=1}^n V_j [G_i \cos(\delta_i - \delta_j) + B_i \sin(\delta_i - \delta_j)] = 0 \quad (4)$$

$$Q_G - Q_D - V_i \sum_{j=1}^n V_j [G_i \sin(\delta_i - \delta_j) + B_i \cos(\delta_i - \delta_j)] = 0 \quad (5)$$

Where, P_G and Q_G are the real and reactive power generation at bus i
 P_D and Q_D are the real reactive power demand at bus i
 n is the total number of buses
 $B_{i,j}$ is susceptance of line i, j

The inequity constraints represent the network load buses, network voltage and GUPFC size limit respectively given by:

$$\lambda_k^m < \lambda_k < \lambda_k^m \quad (6)$$

$$V_i^m \leq V_i \leq V_i^m ; i \in N_B$$

$$(7)$$

$$Q_n^m \leq Q_n \leq Q_n^m$$

$$(8)$$

For $k=1, 2, 3, \dots, N_{bus}-1$, N_B is the total number of buses excluding slack bus, $n=1,2,3, \dots, ND-GUPFC$

PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is a population based stochastic optimization technique developed by social psychologist and electrical engineer in the late 90's. It is inspired by the social behavior of certain groups of animal species. The extensive use of PSO in to many engineering optimization areas is due to its

unique searching mechanism and computational efficiency (Binitha and Siva, 2012). PSO makes use of multiple agents referred to as particles, a cluster of which form a swarm, the particles move around in the search space in search of the optimum solution. Each particle is considered as a point in N-directional space and its 'flying' adjustments is dependent on the flying experience of other particles and its own flying experience (Selvi and Umarani, 2010). PSO has a feature of being flexible and balanced mechanism, these features makes enhancement and adaptation of global as well as local exploration and exploitation possible, in short computational time. Few of the numerous advantages of PSO include; ease of implementation, robustness of control parameters, and its concept is easy when compared to other available heuristic methods of optimization, it also has superior computational efficiency (Park, *et al.*, 2005). As a result, the aforementioned superior features qualify PSO as a highly viable candidate for use when solving optimization problems with multiple-objectives. Figure 2 shows the searching path of PSO.

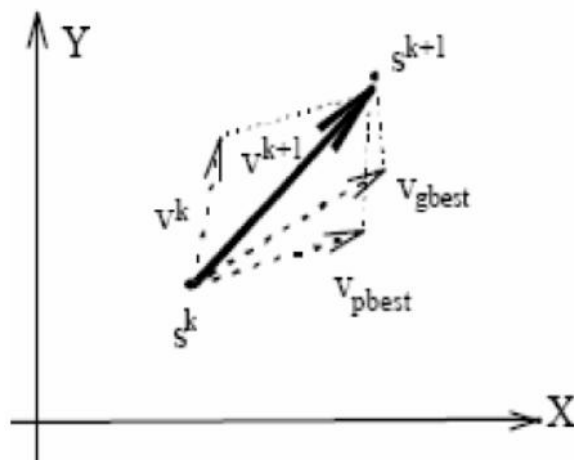


Figure 2: Search Path of PSO (Shende and Jagtap, 2013)



S^k is the Current searching point
 S^{k+1} is the Modified searching point
 V^k is the Current velocity
 V^{k+1} is the Modified velocity
 V_p is the Velocity based on P_{best}
 V_g is the Velocity based on G_{best}

As each particle adjusts its flying, it keeps a record or track of its coordinates which are close enough to the best solution (Fitness) in the solution space that is attained by the particular particle in question. That value is termed Personal best, P_{best} . Also, another best value that PSO keeps tabs on is the best value attained so far by neighboring particles. Which is termed the Global best, G_{best} . The next step after finding the aforementioned two best values i.e P_{best} and G_{best} , is for the particle to update its velocity and positions with the equations below (Shende and Jagtap, 2013).

$$V_i^{k+1} = wV_i^k + c_1 * r_{i1} (P_{bi} - S_i^k) + c_2 * r_{i2} (G_b - S_i^k) \quad (9)$$

$$S_i^{k+1} = S_i^k + V_i^{k+1}$$

$$w = w_m - \left(\frac{w_m - w_m}{it_m} \right) \times it \quad (10)$$

(11)

Where,
 V_i^k is the Velocity of agent i at kth iteration
 V_i^{k+1} is the Velocity of agent i at (k+1)th iteration
 w is the inertia weight
 c_1 and c_2 are the weight factor (0 to 4)
 S_i^k is the Current position of agent i at kth iteration
 S_i^{k+1} is the Current position of agent i at (k+1)th iteration
 it_m is the Maximum iteration number
 iter is the Current iteration number
 P_{bi} is the Personal best of agent i
 G_b is the Global best of the group
 w_m is the Initial value of the inertia weight
 w_m is the Final value of the inertia weight
 r_{i1} and r_{i2} are the random numbers usually chosen between [0,1].

MATERIALS AND METHODS

The proposed PSO approach was implemented on a Nigeria 28-bus transmission network. The flowchart in figure 3 shows how the PSO based method is used in this work.

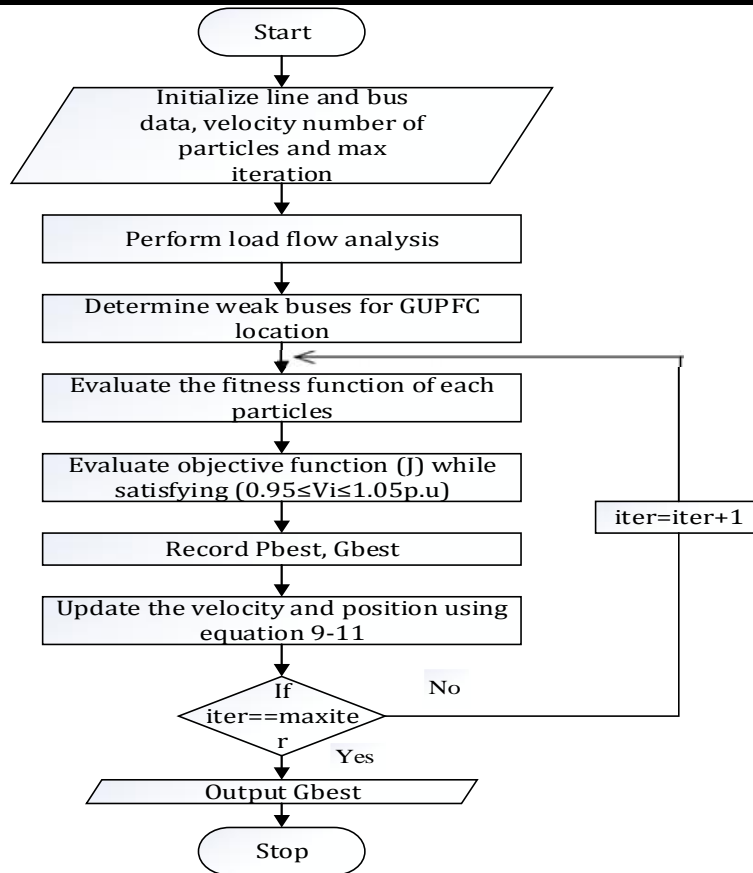


Figure 3: Flowchart of the proposed PSO based method

MATLAB R2017a virtual environment was used for writing the program, which was used for the implementation of PSO based approach for GUPFC allocation. HP 635 Personal Computer with the following specifications was also used:

- Processor: Intel(R) Pentium (R) CPU B950 @ 2.10GHz Dual Core
- Installed Memory (RAM): 4.00GB
- System type: 64-bit Operating system, x64-based processor
- Operating System: Windows 8 pro single language.

Consequently, the network line data and then bus data were loaded, as the power flow analysis for the base case was carried out using Newton-Raphson method. The network voltage constraint was set as 0.95p.u. and 1.05p.u. for minimum voltage (V^{\min}) and maximum voltage (V^{\max}) respectively, while the GUPFC is sized between 0 and 100% of the total network reactive power (kVar) loading. In this paper, the initialization parameters for the proposed PSO based method are presented in Table 1.



Table 1: Parameters Settings for PSO

S/N	Parameters	Values
1	Number of particles	50
2	Number of iteration	50
3	Individual acceleration constant	2.5
4	Social acceleration constant	2
5	Initial inertia weight	0.9
6	Final inertia weight	0.4
7	Velocity	1

RESULTS AND DISCUSSION

In order to verify the effectiveness of the PSO in search for the optimal location and size of GUPFC in transmission networks, the Nigeria 28-bus 330kV network was employed. The single line diagram, line data and bus data for this network are provided in (Adebayo, *et al.*, 2013).

Network Voltage Profile Analysis

The optimal size and location of GUPFC was found to be 109.32MVAR and buses 17-20, 19-20 respectively using PSO technique. A clear improvement in voltage profile of the network with GUPFC

is shown in figure 4. It is clearly observed that buses 9 (0.9489), 13 (0.9399), 16 (0.9498), 19 (0.9487) and 22 (0.9399) considered to have violated the $\pm 5\%$ tolerance margin of voltage criterion. This low voltage is an indication that the network is prone or susceptible to possible voltage instability, but after the placement of GUPFC they increases to 1.0000p.u, 1.0398p.u, 1.0358p.u, 0.9932p.u and 1.0078p.u respectively, thus enhancing the entire voltage profile of the system by 2.49 % as compared to the overall network base case voltage profile.

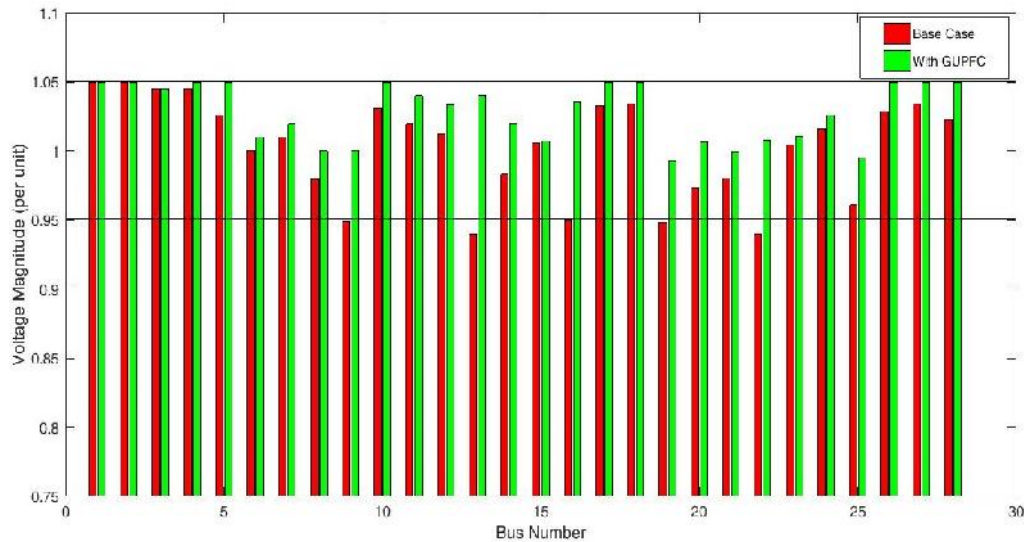


Figure 4: Voltage Profile Result of Nigeria 28-Bus Network

Network Power Loss Analysis

The results of network power losses with and without GUPFC are plotted against their respective line numbers and shown in figure 5. It is observed that the highest loss occurs at lines 8, 17, 22, 28. The base case total power loss of the network is

132.2751MW, but in the presence of GUPFC size 109.32MVar optimally located on the network using PSO, yields a reduction of 91.5486MW representing 30.99% average real power improvement across the entire network.

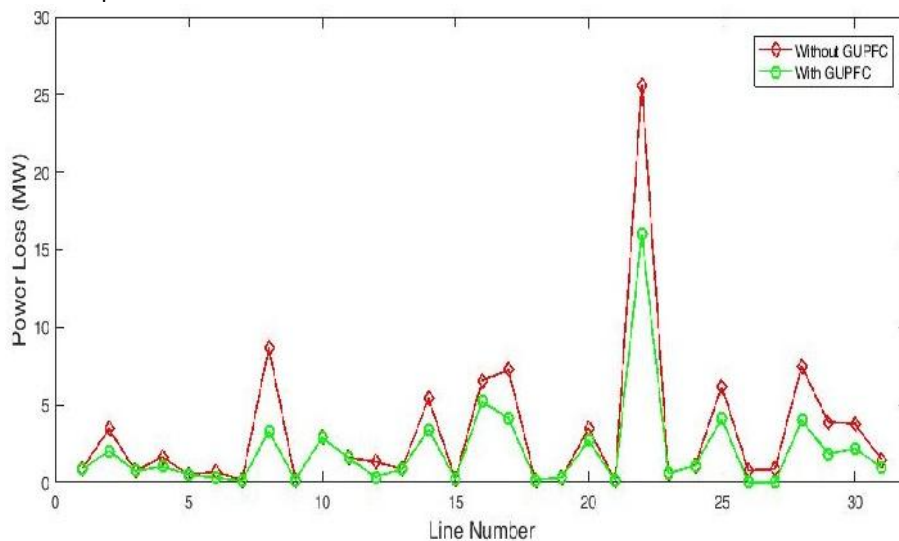


Figure 5: Power flow Result of Nigeria 28-Bus Network

CONCLUSION

This paper has presented a particle swarm optimization based technique for optimal location and sizing of GUPFC in a transmission network. A multi-objective optimization approach comprising of total active power loss and network voltage deviation was formulated and used in the PSO. The effectiveness of the approach was demonstrated on Nigeria 28-bus, 330kV transmission network. As it's evident enough from the obtained results, deployments of GUPFC at optimum point or location has further enhance the network performance due to the significant reduction in losses as well as improvement in the overall network voltage profile.

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