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Load-ability Analysis during Contingency with Unified Power Flow Controller Using Grey Wolf Optimization Technique

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Abstract: Voltage stability enhancement with optimal placement of a unified power flow controller considering load-ability analysis is investigated in this paper. It is essential, because when voltage instability is left unattended, it leads to voltage collapse and, consequently, in a partial or total blackout of the whole network resulting from cascading effect. The optimization process is achieved by increasing the percentage load demand index to the maximum load-ability and under single contingency. This method will be of great benefits to bulk dispatcher of power to plan ahead of how to wheel and deliver power to the end-users during both normal and contingency conditions at the least cost and time. A grey wolf optimization technique is utilised to find the optimal location and sizing of UPFC on the network. The line's voltage stability and load margin are then evaluated with and without UPFC under different loading conditions using optimal power flow technique. The approach's effectiveness is carried out on 31-bus, 330kV Nigeria National Grid (NNG) based on two scenarios: load-ability analysis under maximum loading of the network and load-ability analysis under single contingency. The results show that power can be transmitted to meet the growing energy demand over an existing network during normal and contingency conditions without violating voltage stability by making use of the proposed method in this paper.

Keywords: Grey Wolf Optimization, Line Load-ability, Maximum Loading, UPFC, Voltage Stability.

1. INTRODUCTION

Electrical energy is a crucial ingredient for a country's economic and industrial development; hence, there is an endless demand for this energy [1]. So, it is of central importance for the power industry to guarantee the continuity of a stable, secure, economic, efficient, and reliable power supply at all times. With the rising demand for electrical energy, coupled with population growth and recursive increase in technological development under contingency and restructured market environment, inevitably that voltage instability, line congestion, power losses, frequency collapse, and transient instability will exist on the network [2, 3]. Due to these challenges, transmission lines are being operated closer or beyond their stability limit and the emergence of other associated limits that lead to power system instability[4, 5]. Confronted with these challenges and constraints, power system engineers have been struggling to develop a new and robust device that can deal successfully and swiftly with these constraints limiting network capacity and provides power improvement options. The need to install a robust device in an existing transmission asset to provide an effective, efficient, economic, and environmental friendly way of improving transmission line's power carrying capacity is of utmost importance [6]. This essential task has led to the introduction of advanced power electronics based converters known as Flexible Alternating Current Transmission System (FACTS).

FACTS devices are used to alleviate line congestion, increase power transfer capacity, enhance system security and make power transfers fully controllable by controlling all three power flow parameters, namely, line impedance, voltage magnitude and phase angle [6, 7]. Over the years, these devices have brought to bear new perceptions that network instability and constraints can be solved successfully and promptly. Among the various known FACTS devices, Unified Power Flow Controller (UPFC) is the mostly commonly used, because of its uniqueness to independently and simultaneously provides a super control and regulation of the magnitude of the bus voltage, and power flow via the line where it is attached [8, 9]. Due to the high cost of procuring and installing the FACTS devices, an adequate plan should be geared towards placing it at an appropriate location. FACTS devices' performance depends significantly on the network's location and size [6]. Combining FACTS devices and optimization techniques are the leading method used in modern power systems to curtail and alleviate line congestion efficiently. In this paper, GWO is deployed to locate the best position and sizing of UPFC on 31-bus, 330kV NNG. It is used because of its flexibility, scalability and exceptional ability to balance between the exploration and exploitation in unknown search spaces to give a favourable result and convergence. UPFC is optimally placed on the network to alleviate congestion, power loss reduction, and improved stability of the network etc.

2. THE 31-BUS, 330KV NIGERIA NATIONAL GRID

The 31-bus, 330kV Nigeria National Grid used for this analysis consists of seven (7) generator buses (PV), twenty-four (24) load buses (PQ), and thirty-seven (37) transmission lines. It comprises 6,000km of 132kV lines, 5,000km of 330kV lines, 23km of 330/132kV substations, and 91km of 132/33kV. The following challenges characterize these networks; long transmission lines, fragile grid network, technical hitches of wheeling energy produced from the generating point to the load centers, single and radial circuit network, frequent system collapse, improper configuration of the network, aging and obsolete facilities, overloading, thermal limits violation and poor voltage profile, and lack of ability to regulate some transmission line parameters such as; voltage, and frequency [10]. Technically, these challenges bedevilling NNG can be eliminated by constructing additional generating units and transmission capacity to meet the rising demand to boost the system reliability and stability. However, economic, political, environmental impacts, and construction time have made these measures not to be anticipated. These problems have strongly demanded the optimization and upgrading of the existing network capacity to enable more power transmission during normal and contingency conditions without violating network voltage stability [11-14]. This paper presents a combination of the FACTS device (UPFC) and GWO optimization technique to solve the numerous challenges facing NNG.

2.1 Line Load-ability

Line load-ability is defined as the optimal power transfer capability of a transmission line under a predefined set of operating conditions [15]. Load-ability analysis examines the loading and operating conditions of the network [14]. This analysis estimates the peak power that a transmission line can withstand and permit to flow through it and also reveals various region of the network that can still serve extra loads. Since voltage quality limit affects the power-carrying capacity up to a substantial lengths of the transmission line. In analysing the load-ability of a network, it has been established that there will be areas that will be lightly loaded and can still accommodate additional loads, in contrast, some areas will be heavily loaded, and thereby pressing the network to be operating closer or beyond their stability limit [16]. The following factors limit the loading capacity of a transmission line: voltage-drop, thermal, and steady-state stability limits. Others are voltage stability margin, voltage quality limit, and joule losses limit [17]. The voltage-drop limit is a function of line loading and line characteristics. In contrast, thermal limit depends on the line characteristics and metrological condition of the network location and the steady-state stability reliant on the power system's line characteristics and characteristics of the power system [15]. These issues and other factors result in network voltage instability [18, 19]. Voltage instability is normally regarded as a local phenomenon, but its consequences are widely spread, causing many significant blackouts in the country [20]. Voltage collapse and line overload are still the principal threats to the transmission system [21].

3. MODELLING OF THE UNIFIED POWER FLOW CONTROLLER

The unified power flow controller was first proposed in 1991 by Gyugi [22]. It comprises two switches based on the voltage source converter valves; shunt (exciting-transformer) and series (boosting-transformer), as shown in Fig. 1. Both the exciting and boosting transformers are connected by a standard DC voltage link, signified by the capacitor and two-gate turn off (GTO) converters. Converter 1 (shunt) is connected in parallel to a local bus to be improved through an exciting transformer. This provides the active power needed by Converter 2 at the terminal of the common DC voltage link from the network alternating the local bus's current power system. It also serves as both generator and absorber of reactive power at its AC terminal that is not dependent on the active power emanating from or to its DC terminal. Converter 1 leverage its ability to offer the role of independent advance static VAR compensator by compensating the transmission line's reactive power and consequently provides voltage regulation at the UPFC input terminal. Converter 2 is linked in series to a bus via a boosting transformer. It generates source voltage at fundamental frequency with phase angle ($0 \leq \emptyset_T \leq 2\pi$) and variable amplitude ($0 \leq V_T \leq V_{Tmax}$). The voltage source generated is coupled to a series-connected boosting transformer to the AC transmission line. Amongst the various FACTS devices, UPFC has an exceptional ability to simultaneously and independently control the three parameters of power flow: voltage magnitude, phase angle, and line impedance. This has made UPFC more versatile and widely used than other FACTS devices. Fig. 1 shows a typical operating principle of UPFC. It depicts the steady-state model of UPFC under different loading conditions.

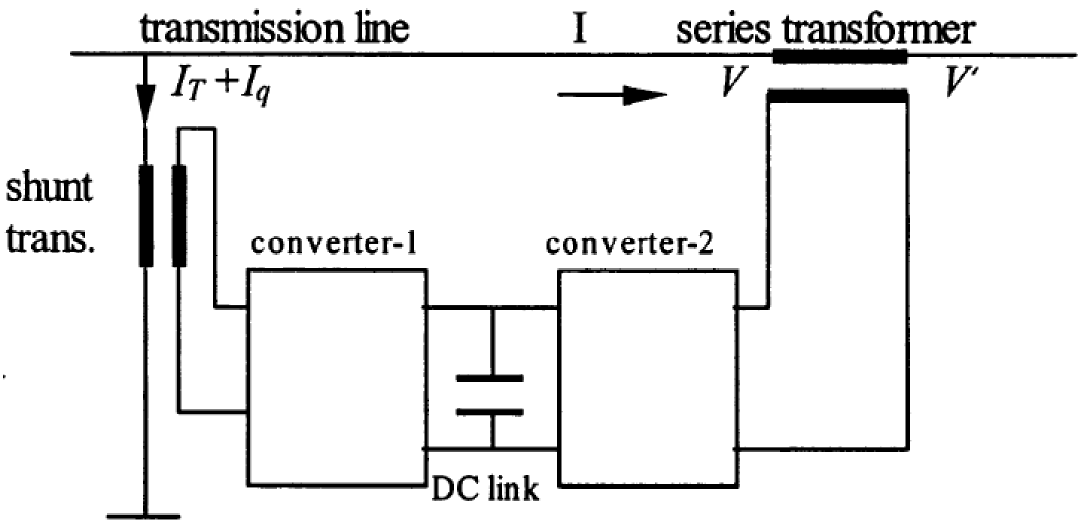

Figure 1: The Operating principle of UPFC [9, 23]

The injected powers ($P_{gi}$and Q_{gi}) at bus-i along with system loading (λ) is given by (1) and (2):

$$P_i = P_{gi} - P_{di}^0(1+\lambda) = \sum_{j\in N_b} P_{ij} \quad (1)$$

$$Q_i = Q_{gi} - Q_{di}^0(1+\lambda) = \sum_{j\in N_b} Q_{ij} \quad (2)$$

Here, active and reactive power demand is represented by P_{di}^0 and Q_{di}^0. The real and reactive power generated at bus-i is denoted by P_{gi} and Q_{gi}. In equations (1) and (2), an even loading of load buses is considered and to be supplied by swing bus, such that allocation of generation among the generators can easily be done by integrating it into this model [9].

3.1 Grey wolf optimization technique

Based on the grey wolf (*Canis lupus*) social hierarchy and hunting characteristics, a metaheuristic algorithm called Grey Wolf Optimization (GWO) technique was developed by [24] in the year 2014. Wolves belong to the Canidae family and they live in a pack of an average size of 5-10. They are divided into four categories in the order of alpha (α), beta (β), delta (δ), and omega (ω) [25]. Figure 2 shows the leadership pyramid of grey wolves. A male and a female known as alphas are the leaders of the pack. The alphas with higher dominance are decision-maker of the pack. They are well-endowed with the capacity to control and manage the pack appropriately by commanding the other lower-level wolves. The three main hunting phases are; tracking the prey, encircling the prey, and attacking the prey. Alpha, beta, and delta carry out the hunting for the pack. Alpha is regarded as the best (fittest) solution as a result its superior knowledge of hunting prey. At the same time, beta is the second-best solution, and delta gives the third-best solution, and gamma is the other candidate solutions. This algorithm has shown the ability to balance the exploitation and exploration of problem where the search space is unknown and yields a favourable result at a speedy rate [24].

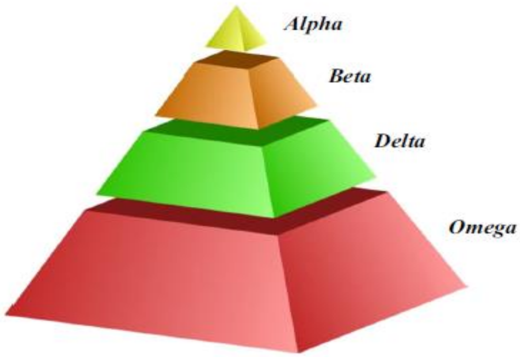

Figure 2: The social hierarchy of grey wolves [26]

(a) Social Hierarchy

Social hierarchy is model mathematically by taken alpha (α) as the best (fittest) solution, beta (β) is considered as the second-best solution, and the third-best solution is named delta (δ). In contrast, the other solutions are considered as omega (ω). The optimization technique is controlled by three wolves, namely; alpha, beta, and delta, while omega is just a follower and babysitter in the pack.

(b) Encircling prey

The first stage in the hunting behaviour of a wolf is to surround the prey; the mathematical model is given by (3) and (4):

$$\vec{X} = |\vec{A} \cdot \vec{P}_{prey}(t) - \vec{P}(t)| \quad (3)$$

$$\vec{P}(t+1) = \vec{P}_{Prey}(t) - \vec{S} \cdot \vec{X} \quad (4)$$

Here; t denotes the current iteration.

$\vec{S}$ and $\vec{A}$ are coefficient vectors,

$\vec{P}_{prey}$ gives the position of the prey, the position of the prey is denoted by $\vec{P}$.The vectors $\vec{S}$ and $\vec{A}$ are mathematical solved using equations (5):

$$\vec{S} = 2\vec{a} \cdot \vec{r}_1 - \vec{a}, \text{ and } \vec{A} = 2 \cdot \vec{r}_2 \quad (5)$$

$\vec{a}$ decreases linearly from 2 to 0, while r_1 and r_2 are the random vector between [0, 1]

(c) Hunting

Grey wolves can detect the exact location of the prey and circle-shaped it. α is the dominant dominance in the hunt and delta, and beta sometimes participates in the hunting. In order to develop the mathematical modelling of this behaviour, alpha (the fittest candidate solution), beta and delta are presumed to have the best knowledge of the precise (optimum) position of the prey. Hence, the first three best candidate solutions achieved are saved (i.e., α, β and δ), and then the other search agents, including the omega (ω) positions are updated using (6) and (7):

$$\vec{X}_\alpha = |\vec{A}_1 \cdot \vec{P}_\alpha - \vec{P}|, \ \vec{X}_\beta = |\vec{A}_2 \cdot \vec{P}_\beta - \vec{P}|, \ \vec{X}_\delta = |\vec{A}_3 \cdot \vec{P}_\delta - \vec{P}| \quad (6)$$

$$\vec{P}_1 = \vec{P}_\alpha - \vec{S}_1 \cdot (\vec{X}_\alpha) \ \ \vec{P}_2 = \vec{P}_\beta - \vec{S}_2 \cdot (\vec{X}_\beta), \quad \vec{P}_3 = \vec{P}_\delta - \vec{S}_3 \cdot (\vec{X}_\delta) \quad (7)$$

$$P_{(t+1)} = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \quad (8)$$

4. OPTIMAL POWER FLOW PROBLEM FORMULATION

The power flow problem is optimized to give the optimal setting of the network control variables in order to adequately supply the power demand by minimizing predefined set of objective functions while sustaining the system physical and operational constraints:

Minimization of Real Power Loss

Minimize $P_L(x, y)$ (9)

Subject to:- $h(x, y) = 0, \ \ g(x, y) \leq 0$

Here, *"h"* denotes the equality constraints which signify a typical load flow equation and *"g"* represents inequality (operating) constraints such as; generator voltages, real and reactive power outputs, and shunt compensation.

$$min\ P_L = \sum_{k=1}^{N_l} [G_k \left(V_i^2 + V_j^2 - 2V_iV_jcos\theta_{ij}\right) \quad (10)$$

The active power loss is denoted by P_L, G_k represents branch conductance *k*. V_i and V_j indicate sending and receiving end voltage magnitudes and phase angle between i^{th} and j^{th}bus is signified by θ_{ij}.

Minimization of Voltage Deviation (VD)

This objective function enhances the magnitude of the line voltage by decreasing the voltage deviation on all P-Q buses. This is defined in (11):

$$F_{VD} = \min(VD) = \min(\sum_{k=1}^{N} |V_i - V_j^{ref}|^2) \quad (11)$$

Here, V_i is the bus voltage at bus-*i* and V_j^{ref} indicates reference voltage limit at bus-*j*.

Equality Constraints

Active and reactive power equality constraints are given by:

$$0 = P_{Gi} - P_{Di} - V_{Gi} \sum_{j \in Ni}^{Nb} V_j \left(G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}\right) \quad for\ i \in N_b \qquad (12)$$

$$0 = Q_{Gi} - Q_{Di} - V_{Gi} \sum_{j \in Ni}^{Nb} V_j \left(G_{ij} sin\theta_{ij} + B_{ij} cos\theta_{ij}\right) \quad i \in N_b \qquad (13)$$

Where N_b denotes total number of buses in a network, P_{Gi} represents total active power generation, P_{Di} is the total power demand, the reactive power generation is Q_{Gi}, Q_{Di} is the reactive power demand, G_{ij} denotes conductance and B_{ij} is susceptance between i^{th} and j^{th}bus.

Operational Inequality Constraints

The voltage, active power, reactive power, transformer and shunt compensator operational inequality constraints for both generator and network are given in terms of lower and upper limits as described below:

$$V_{Gi}^{min} \le V_{Gi} \le V_{Gi}^{max} \quad i \in N_b$$
$$Q_{geni}^{min} \le Q_{geni} \le Q_{geni}^{max} \quad i \in N_b$$
$$P_{geni}^{min} \le P_{geni} \le P_{geni}^{max} \quad k = 1 \dots\dots, NT$$
$$T_i^{min} \le T_i \le T_i^{max} \quad k = 1 \dots\dots, NT$$
$$Q_{shi}^{min} \le Q_{shi} \le Q_{shi}^{max} \quad k = 1 \dots\dots, NT$$

5. RESULTS AND DISCUSSION

This section presents two scenarios: load-ability analysis under maximum loading condition and load-ability analysis under single contingency based on 31-bus, 330kV Nigeria National Grid. This aims to verifying the practicability of this technique at delivering power during both maximum loading and contingency conditions without interruption of supply to consumers. All simulations analyses are done in MATLAB R2017a software using Intel(R) Pentium (R) CPU 2020M with a Dual-Core processor speed of 2.40GHz. The maximum loading occurs at a point where Newton-Raphson has no value (diverged). The network voltage stability is enhanced by the optimal placement of UPFC on the network using the grey wolf optimization technique.

A. Load-ability Analysis at Critical Loading Condition

Table 1 shows the power flow results of 31-bus, 330kV NNG under an increasing percentage load demand index of 39.72% with and without UPFC at 56th iterations. It is observed that the load growth results in huge power losses in line 33 (7-28) by 11.56MW, followed by line 35(17-19) with 6.89MW loss, and line 36(8-29) increased by 4.89MW respectively when compared to the result under normal condition. This results from the extended distance from the generating unit and the nearer critical lines' cascading effects. A total power loss of 210.7861MW is obtained. After optimal placement and sizing of UPFC device using GWO, the network power loss reduces to 145.4235MW, representing 40.6661% power loss reduction with the installation of UPFC device with a reactive power setting -103.3200MVar at bus 19, the UPFC considerably reduced the total power loss on the network.

Table 1: Power flow result of 31-bus, 330kV Nigeria National Grid at critical loading.

Percentage Loading Value	Loss without UPFC (MW)	UPFC Rating (MVAr)	Loss with UPFC (MW)	UPFC Location	Percentage Power Loss Reduction
39.72	210.7861	-103.3200	145.4235	19	31.0090

Figure 3 shows the voltage profile with and without placing the UPFC device under the network's critical loading. It is observed that bus 28 has a minimum base voltage of 0.9031 p.u due to the considerable distance of the bus from the generating unit. When UPFC was optimally placed on the network, it increases the voltage magnitude to 0.9540p.u. Many of the load buses, especially bus 11, 16, 18, 20, 21, 22, 25, and 29, are the overloaded buses and as such closer to their specified lower boundary of 0.95 p.u, which means any slight rise in the load demand, will result in voltage collapse. However, with the optimal placement of UPFC using GWO at Bus 19, it is observed that the magnitude of the voltage profile increased significantly thereby enhanced the stability margin of the network and allow extra power to be transmitted over the existing network.

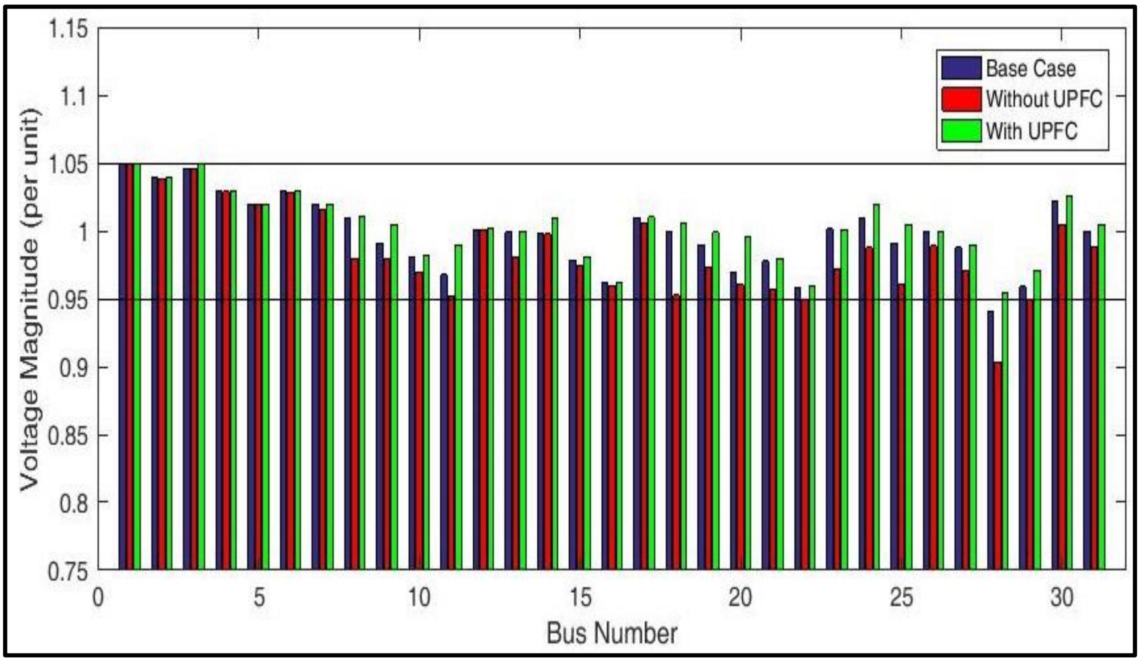

Figure 3: Voltage profile results under critical loading condition

B. Heavy Reactive Loading with Single Generator Outage

Table 2 shows the performance of GWO during a heavy reactive loading under a single generator outage condition. The power flow result revealed that, the loss of generation at Bus-7 increases the losses at line 6 to 85.54MVAr from the initial base case with succeeding cascading failures on lines 7 (4-21) and 31(6-27) due to their nearer connections to the critical lines. Also, at line 36(8-29), a loss of 155MVar, the highest reactive power loss occurs due to the source's network topology and distance. Bus 28 is evidently the weakest and most vulnerable node, due to its lowest permissible reactive load of 0.4154MVAr in the presence of contingency. It is also evident that the generator outage condition increases the network's total power losses compared to normal conditions. It also reveals that with the installation of UPFC on the network, apparent power loss at the 6th line reduces from 105.54MVAr to 32.22MVAr representing 69.47% loss reduction, and at branch 36, a loss of 155MVAr reduces to 28.95MVAr representing 81.32%. This enhancement is witnessed in the whole network, which has demonstrated the UPFC device's capability to control voltage magnitude at a bus and power flow in a line where it is installed.

Table 2: Power flow result for 31-bus, 330kV NNG during generator outage

Percentage Load Increase	**Losses without UPFC (MVar)**	**Rating of UPFC (MVAr)**	**Losses with UPFC (MW)**	**UPFC Location**	**Percentage Power Loss Reduction**
42.30	250.5430	-189.98MVar	164.6500	24	34.28

In order to analyse the steady-state stability condition of the network under a heavily loaded reactive power and a single generator outage, bus 17 is loaded to a maximum load level of 42.30%, and generator-7 is made out of service to create contingency. High severity is witnessed when the outage of the generator at bus-7 occurred. Figure 4 shows the voltage profile of heavy reactive loading of bus 17 at 42.30% with and without UPFC installation. The major voltage sag occurred at bus 28 (0.9092) due to loss of reactive power that should originates from generator at bus-7 that was made out of service. From this Figure 4, it is identified that, simultaneous heavy loading and generator-7 outage have more effects on the voltage magnitudes. This is due to the lack of reactive power that generator-7 ought to support the network. With an optimal installation of the UPFC device of reactive power setting -189.98MVar at Bus 24, all voltage at the buses are augmented and stabilized to the tolerable limit.

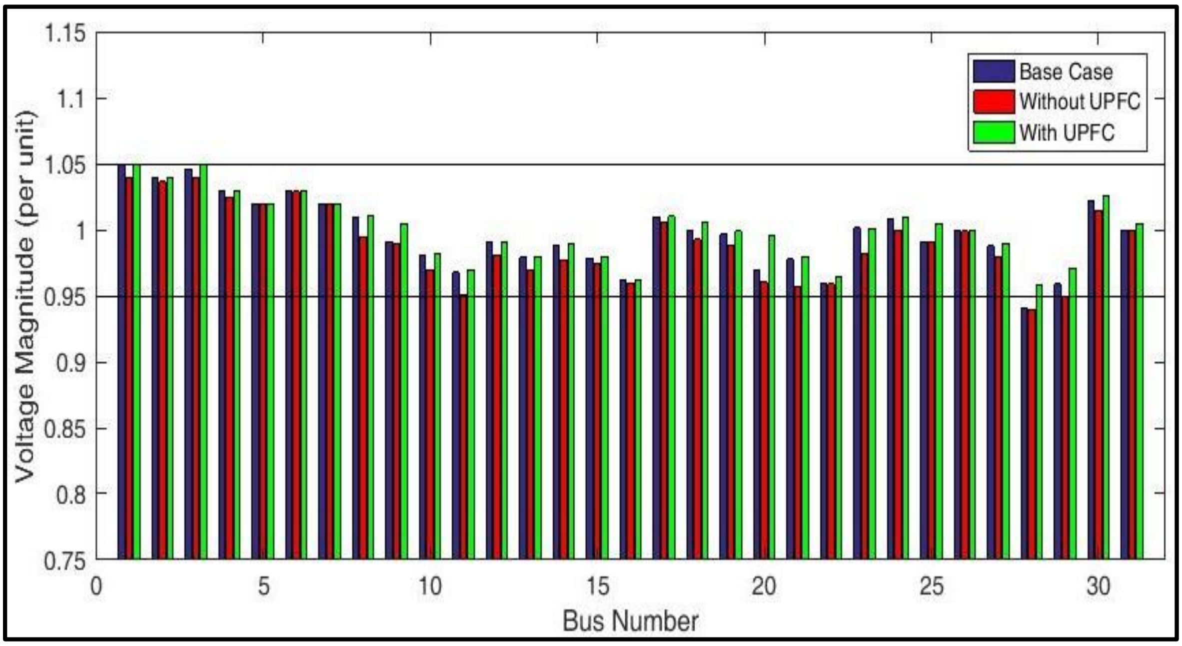

Figure 4. Voltage profile under heavily reactive loading at Bus 17 with Single Generator Outage

C. Heavy real power loading with Single (N-1) line outage

Table 3 shows the performance of GWO for a single line outage condition of 31-bus, 330kV NNG. The most sensitive line 28 is made out of service, and a maximum load-ability is obtained at 42.76% at 47th iterations. An overall power loss of 180.2350MW is obtained. After optimal placement of the UPFC device, the power loss reduces to 95.4500MW, representing a 47.0414% loss reduction. The optimal installation of UPFC of reactive power setting is -89.7500MVar on bus 19. The UPFC considerably reduced the total power losses on the network.

Table 3: Power flow result for 31-bus, 330kV NNG under single line outage

Percentage Max. Loading Value	Losses without UPFC (MW)	Rating of UPFC (MVAr)	Losses with UPFC (MW)	UPFC Location	Percentage Power Loss Reduction
42.75%	180.2350	-89.7500	115.4500	19	47.0414

The most sensitive line 28 is made out of service, and a maximum load-ability is obtained at 42.76% at the point of voltage collapse. GWO was used for the optimal location and sizing of the UPFC device by considering all the contingency. The result shows that buses 22 (0.9476) and 28 (0.9092) have the highest voltage sags. After installing the -89.7500MVAr size of UPFC on the network at bus 19, the voltage sags experienced was adequately compensated through the proper injection of sufficient reactive power to the network to maintain a stable network by keeping all the buses within the acceptable limit. The critical voltage occurs on bus 28 (0.8999 p.u), resulting from the bus's long distance from the generating unit. The optimal installation of UPFC at bus 19 normalized all violated voltages as shown in Fig. 5. It is evident from the foregoing, that UPFC can improve power flow of a transmission line, by reducing the network power losses and enhance voltage stability.

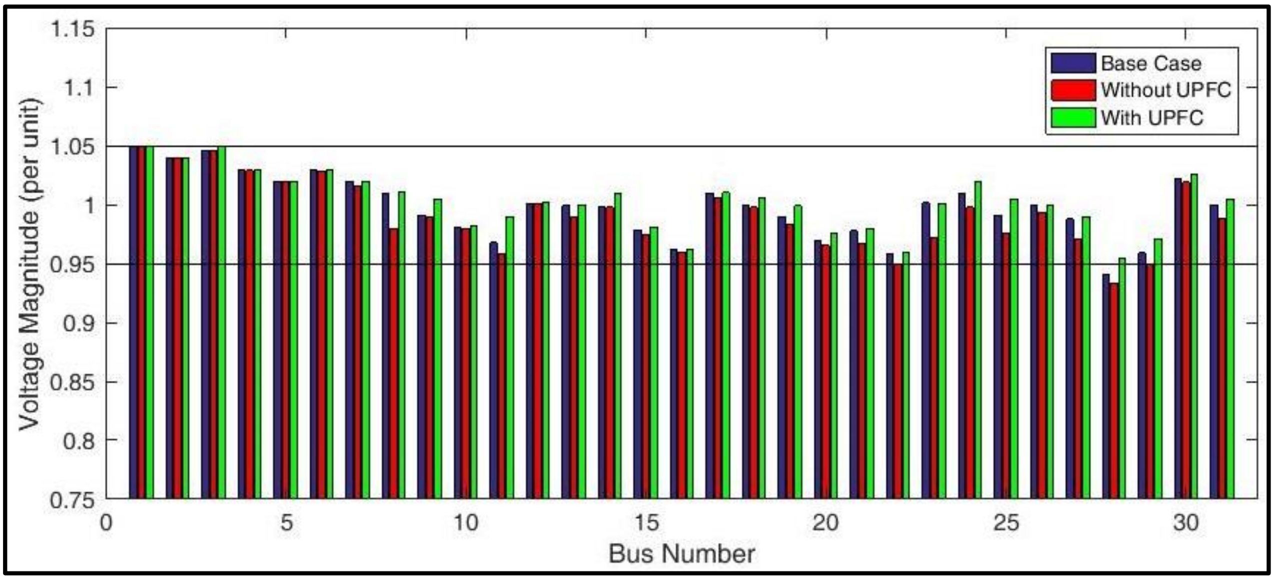

Figure 5: Voltage profile under real heavy load with a single (N-1) line outage

6. CONCLUSION

This paper proposes a nature-inspired metaheuristic grey wolf optimization technique for optimal location and sizing of UPFC on 31-bus, 330kV Nigeria National Grid test system for power loss minimization and voltage deviation reduction. Optimal power flows at steady-state analyses are performed to determine the system performance of the proposed GWO algorithm on the test system under different load variations and contingency for a voltage control reference between 0.95p.u. to 1.05p.u. The results are evaluated based on two scenarios: load-ability analysis under maximum loading of the network and load-ability analysis under single contingency. The results show that using the FACTS device (UPFC) at an optimal location on the network, yields significant reductions in power loss and minimize voltage deviation compared to the base case without the FACTS device. It is also evident that more power can be wheeled and delivered to meet the ever-growing demand over an existing transmission asset during both normal and contingency condition without violating the voltage stability by using the proposed method in this paper.

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