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Metaheuristic-Based Optimal Placement and Sizing of Solar PV and UPFC in Nigeria's 330 KV Transmission Network

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***Abstract*— The major issue that exists in the Nigerian power system network has been voltage instability. it has resulted to voltage collapse and blackout. In this paper, the use of solar photo voltaic cell (PV) system and unified power flow controller (UPFC) flexible alternating current transmission system (FACTS) were examined for the improvement of voltage stability of the Nigerian 330 kV real time power system network in south eastern region. The system was modeled and simulated using power system analysis toolbox (PSAT) software and the outcome implemented in Harris Hawks Optimization (HHO) for the determination of the optimal placement of solar PV and UPFC and then optimal sizing for the solar PV system. From the results generated, it was observed that the optimal location for the solar PV placement was in bus 3 (New heaven) and that of the UPFC allocation was on line 2 which was the transmission line connecting bus 2 and bus 3 (Onitsha TS to New-Heaven TS). The voltage profile showed that none of the buses attained the acceptable voltage level of between 0.95pu and 1.05pu but with the strategic location of the solar PV and UPFC, the voltage profile improved and the voltage dynamics were enhanced. The outcome of the voltage stability index (VSI) showed that Solar system had 98.47% voltage stability improvement while UPFC had 96.33%. This implied that solar system had a better performance than the UPFC.**

Keywords*— voltage stability; voltage profile; UPFC; Solar profile; VSI; PSAT; HHO; optimal allocation and sizing

I. INTRODUCTION

The rising demand for a sustainable and reliable power, coupled with the constant population growth, industrial expansion and the transition towards low carbon energy systems, has increased and intensified the need for an efficient and resilient transmission network worldwide [1]. Voltage stability has been known to become the most vital operational concerns in the modern electricity systems because the inability of a power system network to maintain acceptable voltage level following the occurrence of disturbance and under abnormal conditions would result to voltage collapse and a possibility of widespread blackout [2, 3]. The power system transmission network with inadequate reactive power support, heavily loaded corridor and long transmission distances are always susceptible to power system voltage instability making improvement of voltage stability an important objective in the power system planning and operation [4, 5]. The forecasting of electricity generation and demand is essential for effective power system planning and operation. [6] investigated electricity generation forecasting in Nigeria using linear, quadratic polynomial, and nonlinear least-squares models implemented in MATLAB. Their study highlights the relevance of historical electricity data in predicting future power system conditions for system stability.

The integration of Renewable energy especially the solar photovoltaic (PV) generation system has evolved and emerged as an efficient strategy for enhancing the power system performance while also supporting the sustainability of the energy development [7, 8]. Nigeria as a country possesses one of the major solar irradiation potentials in Africa and across the globe, making implementation of the large-scale solar PV integration economically and technically attractive. When properly sized and strategically allocated solar PV generation can mitigate power loss, reduce transmission loading, improve system reliability and enhance voltage profiles. But, oversizing and inadequate placement of the solar PV introduce reverse power flows, resulting to operational uncertainties and leading to voltage fluctuations that can adversely affect the stability of the power system [9]. Hence, determining the optimal sizing and location of the solar PV system remains a critical optimization problem in the planning of the transmission network [10]. [11] assessed and ranked the photovoltaic energy

potential of ten local government areas in Akwa Ibom State, Nigeria, using NASA meteorological data and PVSyst simulation software. Their results showed that Uyo had the highest annual energy output of 12,422 kWh, while Uruan recorded the lowest at 10,591 kWh. This study demonstrates the importance of assessing solar energy potential when planning renewable energy integration.

Flexible alternating current transmission system (FACTS) devices remain indispensable tool for the enhancement of voltage stability in the heavily loaded power system transmission networks [12, 13]. Among the FACTS devices, the unified power flow controller (UPFC) is essential as it offers the most comprehensive control mechanism by regulating the transmission line voltage magnitude, phase angle and impedance [14, 15]. The multi-functional capability of the UPFC enables the FACTS devices to enhance the voltage profiles, minimize congestion, increase transmission capacity, control reactive power flow and improve steady state and transient stability. Several studies on Nigerian 330 kV power system network have shown that optimal location and adequately tuned UPFC devices significantly improves voltage stability margins while minimizing transmission losses and maximizing network load ability [16, 17].

Metaheuristic optimization approaches have also gained adequate attention as they are being utilized in solving complex power system optimization issues due to their search ability, ability to avoid local optima and robustness [18]. Algorithm such as Artificial bee colony, particle swarm optimization, cuckoo search, harris hawks optimization and other nature inspired approaches have shown superior performances in optimal sizing and placement of the renewable systems and FACTS devices [19]. When compared to the traditional mathematical optimization methods, metaheuristic techniques provide faster convergence, show greater flexibility in handling non-linear objectives and enhanced solution quality and multiple operational constraints [20].

II. Literature Review

In [21] the authors carried out investigation of the transfer capability of the Nigerian 330 kV, 58-bus network with the major objective being to determine how FACTS could enhance the power transfer performance of the transmission network. The paper employed NEPLAN application and MatLab computation analysis to examine the thyristor-controlled series capacitor (TCSC), UPFC and interline power flow controller (IPFC) configurations. The results generated demonstrated that FACTS integration enhanced the transmission transfer capability, with the implementation of UPFC generating a superior performance when compared with IPFC and TCSC. The paper failed to investigate the implementation of coordinated UPFC and solar PV sizing and placement and also failed to utilize metaheuristic optimization. [22] carried out an investigation on the placement of the UPFC for the voltage stability improvement in the Nigeria's southern 330 kV network. the optimal location for the UPFC placement was obtained with particle swarm optimization (PSO) technique. The results generated indicated improved voltage stability performance. But, solar PV was not considered and simultaneous optimization of UPFC and PV sizing and allocation were unaddressed. [23, 24] evaluated the integration of renewable energy for the improvement of voltage stability and power transfer capability. Newton-Raphson load flow analysis was utilized. The outcome showed that solar PV enhanced the weak bus voltages and mitigated the active power losses. But, the study failed to compare the outcome of solar PV with UPFC and metaheuristic optimization were not utilized.

The authors in [16] carried out investigation on the integration of renewable energy into the Nigeria's 330 kV network in improving the voltage stability, mitigating the losses and improving the power transfer capability. Simulation outcome showed improved voltage performance and reduced losses following the utilization of solar PV integration. But, the coordinated Solar PV-UPFC optimization, capacity sizing, optimal locations with metaheuristics techniques were not carried out. Also, the authors in [25] examined stability improvement on the Nigerian South-South 330 kV network. The UPFC Simulation model improved the voltage stability performance of the power system network. The work did not consider optimal sizing, allocation and metaheuristic optimization were not considered in the research.

In this paper, the optimal sizing and location of Solar PV and UPFC on Nigerian 330 kV power system transmission network in south-eastern region of the Nigeria for voltage stability enhancement using Harris Hawks Optimization (HHO) will be investigated. The optimization approach will utilize and identify the most suitable location for the location of the UPFC and solar PV systems with power flow parameters, voltage dynamics and voltage stability index (VSI) being the indicators utilized in measuring their performance.

III. Methods

The Nigerian 330 kV power system network remains a strategic component of the Nigerian national grid that is tasked with transmitting large amount of electricity from the generation stations to the load stations and substations across the country. The South eastern network which is the case study comprises of generation and load stations. The generation stations are Alaoji and Okpai and the load stations are Ugwuaji, New Heaven, and Onitsha. These are interconnected from the generation stations to the load stations. These interconnected lines also improve power transfer capacity, provide operational flexibility and enhance system reliability under the varying loading conditions. But the power system network in the region continues to experience challenges such as transmission congestions, voltage instability, increasing demand and reactive power deficiency, leading to the reinforcement of the power system network and implementation of the FACTS, renewable energy and advanced optimization technologies for the enhancement of power quality and voltage stability.

The mathematical model for the active power flow is given as;

$$Pi = \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \cos(\delta i - \delta j - \theta ij) \quad (1)$$

where: Pi represents active power injected at bus, V_i, V_j represents bus voltage magnitudes, Y_{ij} represents element of the bus admittance matrix, $\delta i, \delta j$ represents voltage phase angles and θij represents admittance angle.
The mathematical model for the reactive power flow is given as;

$$Qi = \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \sin(\delta i - \delta j - \theta ij) \quad (2)$$

where Qi represents the reactive power injected at bus i.
The equation for the Transmission Line Real Power Loss is obtained as;

$$P_{loss} = \sum_{(i,j)} G_{ij} (V_i^2 + V_j^2 - 2V_i V_j \cos(\delta i - \delta j) \quad (3)$$

where: G_{ij} represents transmission line conductance and P_{loss} represents total real power loss in the network.

The data for the Nigerian 330 kV data for South Eastern region is obtained from the National Control Center at Osogbo, Osun State.

The bus data for the power system network is presented in Table 1 and the line data is presented in Table 2.

Table 1: Bus data

Bus number	Bus Name	Bus type	V (pu)	Voltage angle
1	Okpai GS	PV	1.00	-3.88
2	Onitsha TS	PQ	1.00	-2.08
3	New Heaven TS	PQ	1.00	-1.27
4	Alaoji TS	PQ	1.00	-1.87
5	Alaji GS	PV	1.00	0.00

Table 2: Line data

Line number	From bus	To bus	Distance (km)	Circuits	Resistance (pu)	Reactnace (pu)
1	1	2	56	2	0.0051	0.0048
2	2	3	96	1	0.00051	0.0041
3	2	4	138	1	0.0492	0.4220
4	4	5	5	2	0.0039	0.0291

The data in Table 1 and Table 2 are utilized in the modeling of the power system network in power system analytical toolbox (PSAT) shown in Fig. 1.

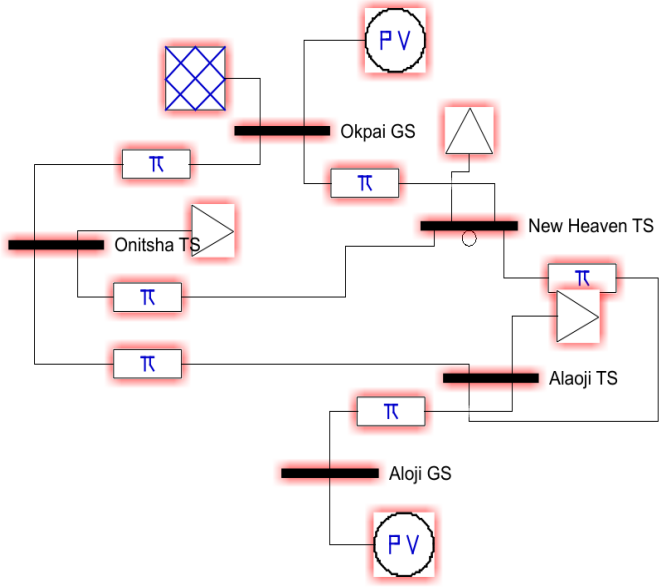


Fig 1: PSAT model of the power system

The mathematical model of the solar PV power output is given as;

$$P_{PV} = P_{rated} \left(\frac{G}{G_{ref}}\right) [1 + \alpha_P (T_c - T_{ref})] \quad (4)$$

where: P_{PV} represents Solar PV output power (MW), P_{rated} represents Rated PV capacity (MW), G represents Actual solar irradiance (W/m²), G_{ref} represents Reference irradiance, normally 1000 W/m², α_P represents PV power temperature coefficient (1/°C), T_c represents PV cell temperature (°C) and T_{ref} Reference cell temperature (°C)
The PV Cell Temperature is given as;

$$T_c = T_a + \frac{NOCT-20}{800} G \quad (5)$$

where: T_c is the cell temperature (°C), T_a Ambient temperature (°C), NOCT represents Nominal operating cell temperature (°C) and G represents Solar irradiance (W/m²).
The Solar PV Reactive Power Capability is given as;

$$Q_{PV} = \pm\sqrt{S_{PV}^2 - P_{PV}^2} \quad (6)$$

where: Q_{PV} represents Reactive power supplied/absorbed by the PV inverter (MVAr), S_{PV} represents Apparent-power rating of the PV inverter (MVA) and P_{PV} Active PV power output (MW).
The UPFC series converter is given as;

$$V_{se} = V_{se}(\cos\theta_{se} + j\sin\theta_{se}) \quad (7)$$

where V_{se} represents the series voltage magnitude that was injected (pu) and θ_{se} represents the phase angle of the injected voltage (degrees).
the current signal with the UPFC injected voltage V_{se} is presented and given as;

$$S_{ij} = \frac{V_i + V_{se} - V_j}{R_{ij} + jX_{ij}} \quad (8)$$

where V_{se} represents the UPFC injected voltage, Vi and Vj represents the sending and receiving voltage respectively, R_{ij} represents active power flow and X_{ij} represents the line reactance.
The Harris Hawks Optimization (HHO) objective function model for the optimal placement of UPFC and solar PV and sizing of the PV was given as;

$$F(X) = w_1\left[\frac{P_{loss(X)}}{P_{loss\ base}}\right] + w_2\left[\frac{\Sigma_{i=1}^{Nb}(V_i(X)-1)^2}{(\Sigma_{i=1}^{Nb}(V_{ibase}-1)^2)}\right] + w_3\left[\frac{VSI_{base}}{VSI_{min(X)}}\right] \quad (9)$$

where VSI represents voltage stability index.
Equation 9 obtained the location and sizing for the solar PV and also determined the same location, series angle and suitable shunt reactive power for the UPFC. The optimization was simulated using matlab and the results obtained are presented in the result section.

IV. RESULTS

The outcome of the optimal location and sizing of Solar PV and UPFC is presented in Table 3.

Table 3: Harris Hawks Optimization (HHO) outcome

Optimum parameters	Optimum outcome
Optimum location (solar PV)	New Heaven
Optimum solar PV sizing	New Heaven
Optimal location for UPFC	Line 2 (line between Onitsha and New heaven)

Based on the outcome of the HHO optimization, the solar PV of power rating 287.64 MW is implemented in the New-heaven station and the UPFC FACTS is implemented on the transmission line connecting bus 2 and bus 3.
The voltage profile of the power system with and without UPFC and Solar PV is shown in Fig. 2.

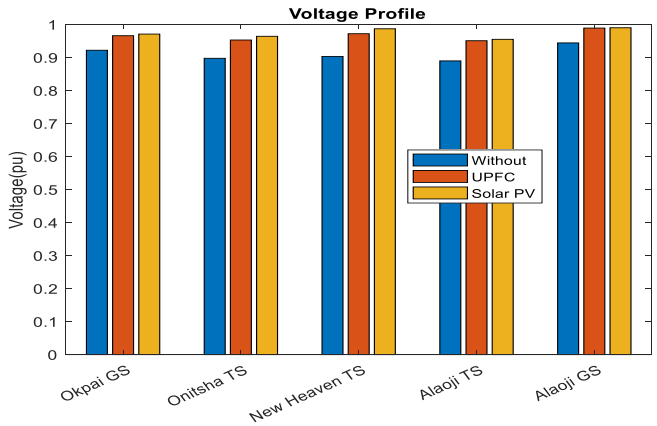


Fig 2: Voltage Profile of the power system without and with UPFC and Solar PV

From Fig. 2, it is observed that the voltage profile of the power system network without solar PV nor UPFC had their voltage magnitude values not within the required range of 0.95pu to 1.05pu. However, the introduction of UPFC and solar system improve the voltage profile with all the buses having their voltage values within the acceptable range though solar PV had a better outcome than the UPFC.
The dynamic responses of the voltage profiles for Okpai and Alaoji generating stations (GS) are presented in Fig. 3 and Fig. 4.

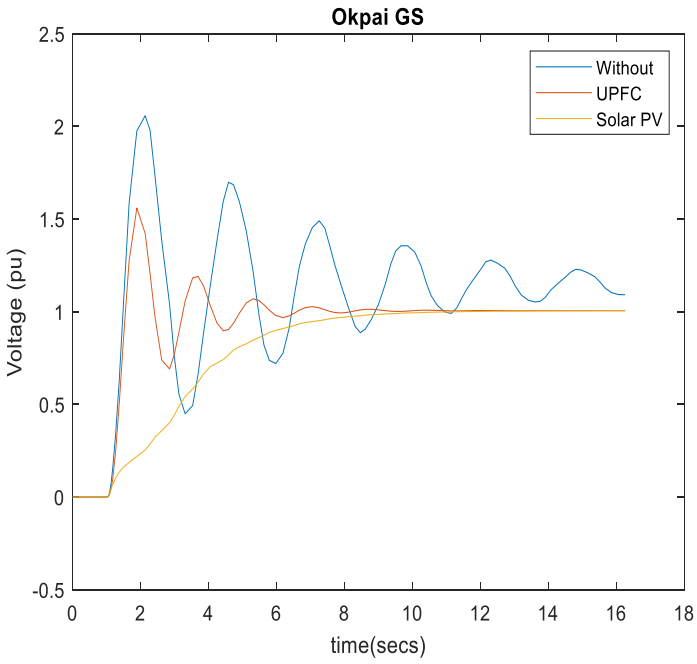


Fig 3: Dynamic response of Okpai GS

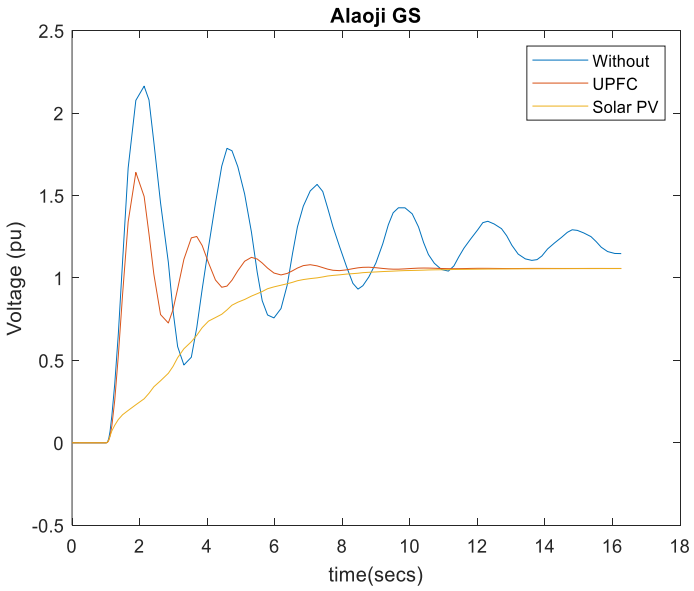


Fig 4: Dynamic response of Alaoji GS

Figs. 3 and 4 show the dynamic responses of the power system network with the aim of determining the

performance of UPFC and Solar PV in improving the voltage stability of the power system. it is observed that the optimal location of solar PV and UPFC improved the system stability of the network as is evidence in the settling time and minimizing both the undershoot and overshoot of the sinusoids. The performance of UPFC and solar PV is shown in the barchart of the voltage stability index (VSI) presented in Fig. 5.

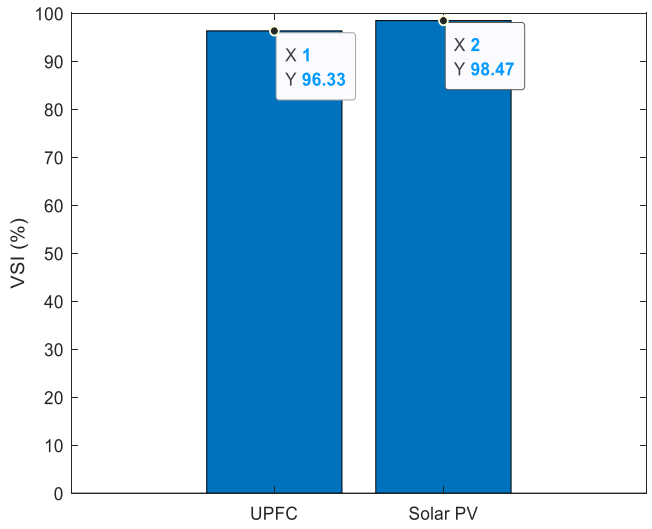


Fig 5: Bar chart of the VSI

From the outcome of the VSI presented in Figure 5, it is observed that solar PV had a better voltage stability enhancement with a VSI value of 98.47 %.

V. CONCLUSION

UPFC FACTS controllers and solar system network were utilized in the improvement of the voltage stability of the Nigerian 330 kV network in south eastern region of the Country. The power system network data was obtained from NCC, Osogbo in Osun State and modeled in power system analysis toolbox (PSAT). The outcome of the simulation was utilized in the HHO technique for the determination of the optimum location for the implementation of solar PV and UPFC and for the optimum sizing of the solar PV system. The UPFC was implemented in line 2 while the solar system was implemented in bus 2. From the results it was observed that the implementation of UPFC and solar system improved the voltage profile of the power system network and improved the dynamic responses by improving the settling and mitigating the overshoot and the undershoot. From the VSI, it was found that solar PV system performed better than the UPFC. Hence, solar system should be strategically implemented for the improvement of the voltage stability in Nigerian 330 kV network, south eastern region of the country.

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