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Application of SSSC for Voltage Stability Improvement in the Nigerian 330 kV Transmission System using Particle Swarm Optimization Technique

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ABSTRACT: Load imbalance has always been a major cause of voltage instability of the power system network and increase in voltage instability affects the power system reliability. In this paper, static synchronous series capacitor (SSSC) FACTS device was implemented to improve the voltage stability in the Nigerian 330 kV transmission network using particle swarm optimization (PSO) technique. Modelled power system network in the power system analysis toolbox (PSAT) is simulated to determine the existing power flow analysis and the level of instability in the power system generation plants situated in the Northern region. The outcome of the power flow is thereafter, optimized with PSO by generating the relationship with a high prediction accuracy between voltage at each location and an inter-linked transmission line distance of the 330kV. The model was generated with least square method and the high prediction accuracy determination was carried out with R-square value of the polynomial order. The best model was optimized and the entire computations were carried out in MatLab resulting in the determination of the optimal location which was between Jebba transmission and Shiroro generation stations. SSSC FACTS controller was implemented on the optimized transmission line and the simulation results showed that the introduction of SSSC improved the voltage stability of the power system network.

KEYWORDS: FACTS, Matlab, Polynomial order, Power flow, PSAT, PSO, R-square, SSSC, Voltage stability

I. INTRODUCTION

The economic growth and development of any nation are intrinsically tied to the availability of energy (Omoroguiwa & Okpo, 2015). Performance evaluation of asynchronous motor, dynamic behaviour and fault resistance of induction motor investigated in (Okpo, Okoro, Awah & Akuru, 2019; Okpo, Okoro, Awah & Akuru, 2020; Abunike, Umoh, Okpo & Okoro, 2020), has given access to a reliable electricity supply which plays a pivotal role in empowering individuals and facilitating personal and economic development. The Nigerian power system network just as the power system across the world, comprises of transmission system, generation systems and distribution systems (Nelson & Odion, 2023; Edifon, Nkan, & Ben, 2016; Okpo & Nkan, 2016). It has been found that the rate of load demand is greater than the amount of electricity generated and this has cumulated into the high rate of the existence of voltage instability (Olanite, Tola, Nwohu, & Adegboye, 2023; Nkan & Okpo, 2016; Oduleye, Nkan, & Okpo, 2023). Other factors that causes voltage instability in the power system network includes; imbalance of the reactive power between the power supply and the load demand which occur due to increase in excitation limit of the generator, large occurrence of inductance on the transmission line network (Izuegbunam, Okafor, & Ogbogu, 2011; Okoro, et al., 2022). The Nigerian power generation systems generates power at voltage ratings of range 16kV to 25kV and then stepped up to the transmission voltage level of either 132 kV or 330 kV for onward transmission to the national grid hence, confirming that the major transmission voltage rating in the Nigerian power system network includes the 132 kV and the 330 kV networks (Olarewaju, Ogunjuyigbe, Ayodele, Mosetlhe, & Yusuff, 2023; Awah, Okoro, Nkan, & Okpo, 2023; Okpo, Nkan, Okoro, & Akuru, 2021). This implies that when the generating plants generates electricity, the voltage rating are increased to either 330 kV (for longer distance transmission) or 132kV. Other transmission voltage rating for shorter distances are 11 kV and 33 kV. The transmission voltage stability is affected due to high rate of power flow congestion as a result of high and constant increase in load demand (Negnevitsky, Voropai, Kurbatsky, Tomin, & Panasetsky, 2013). In the real power generation system, the occurrence of voltage instability is usually caused by the imbalance of transmission capability of the power system network, increase in the generation plant reactive power, exceeding the voltage control limits, and inadequate monitoring of the voltage sensitivity as a result of load increase(Das & Panigrahi, 2020; Zhang, Fu, Diao, Sheng, & Jia, 2018). Therefore it can be seen that the voltage stability problems in the modern Nigerian power system network is an issue related to existing power system constraints and increase in voltage collapse, hence, the introduction of flexible alternative currents transmission system (FACTS) which has been studied and found to be essential in the improvement of the voltage stability by effective control of the active and reactive power (Li, et al., 2020; Huang, Ma, & Wang, 2014; Trişţiu, Iantoc, Poştovei, Bulac, & Arhip, 2019). The types of FACTS that are deployed for voltage stability improvement has been found to be any FACTS device with series components. Shunt FACTS controllers increase the stability of the system by improving the power flow of the transmission network (Constante & Wang, 2018; IanŢoc, Bulac, PicioroagĂ, Sidea, & Trişţiu, 2021; Hu, et al., 2019; Otuo-Acheampong, Rashed, Haider, & Mensah, 2022). In this study, the static synchronous series compensator (SSSC) FACTS controller is deployed and utilized in voltage stability of the Nigerian 330 kV transmission system of the northern Nigeria.

II. REVIEW OF RELATED LITERATURE

In (Nkan, Okoro, Awah, & Akuru, 2019; Abunike, Umoh, Nkan, & Okoro, 2021; Innocent, Nkan, Okpo, & Okoro, 2021), the authors utilized voltage collapse predictive point which was centered on the quadratic line voltage stability index (q-LVSI) and the machine earning auditory intelligent technique (AMI). The proposed model method was applied to the 30 bus network of the Nigerian 330 kV transmission network and the outcome of the model was validated with group method of data handline time series model (GMDHtime-series) which was a polynomial model utilized for the fitting of the artificial neural network model based on the inductive network learning and self-organization system. The outcome showed that AMI model and GMDHtime series models had an acceptable increased system stability of the power system network. (Nkan, Okoro, Obi, Awah, & Akuru, 2019; Ezeonye, Okpo, Nkan, & Okoro, 2020)in their works examined the essence of utilizing wind turbine system integrated to the permanent magnet synchronous machine for the voltage stability improvement of the Nigerian 330 kV power system network. Ant colony optimization technique was deployed to size the wind turbine system that would improve the voltage stability of the system when integrated into the power system network. The outcome with ant colony projected that a wind turbine power rating of 100 MW and convention power plant of 197 MW would control as much as 150 % increase of the load demand and the voltage stability was increased by 3.4%. The authors in (Nkan, Okoro, Awah, & Akuru, 2019; Innocent, Nkan, Okpo, & Okoro, 2021)utilized Newton Raphson power flow analysis in the determination of the power flow of the Nigerian 330 kV network and ODE 45 of Matlab programmed functions were deployed in determining the transient stability of the power generation plants. The major parameter considered was the level of voltage violation of the power system generation plants. The outcome of the results suggested the need to install additional power generation system to match with the load demand so as to minimize the rising load demand which was projected to reduce the voltage instability of the system. In (Nkan, Okpo, & Okoro, 2020; Williams, Okpo, & Nkan, 2023), the authors in their research works improved the voltage stability of an IEEE 14-bus, Nigerian 48-bus network with increasing integration of solar system network and continuation power flow. PSAT and DigiSILENT were utilized for the modeling of the power system network while MatLab was utilized in the performance of the computations of the system. The outcome of the simulations showed that the penetration of solar system in the power system network improved tha voltage stability of the power system. This was achieved by increasing the real power of the solar system upto 10%. (Nkan, Okpo, Akuru, & Okoro, 2020; Ezeonye, Nkan, Okpo, & Okoro, 2022)also utilized a method that was dependent on power network integration characteristics of the power system network for the improvement of the voltage stability of the network. The proposed method utilized admittance matrix between load to load bus in inter connected power system of the Indian power system network. Furthermore, the author applied eigen matrix in the sub matrix of the admittance matrix that was partitioned in the generation and load buses. The model was also tested on the IEE 30-bus system. The outcome presented showed that the proposed model improved the voltage stability of the power system. In (Natala, Nkan, Okoro, & Obi, 2023; Adebayo & Sun, 2021; Dong, Xie, Zhou, Shi, & Jiang, 2016)the authors proposed the use of integrated high-side-var-voltage control (IHSV 2C) for power generation plants to obtain the end powers of the systems. Hence, the use of IHSV 2C involves improvement of the voltage stability with a voltage control point (VCP), which usually occur by regulating the voltage reference point that improves the VAR support improving the voltage stability of the power system. The outcome showed that the use of IHSV 2C improved the voltage stability of the power system. In (Nkan, Okpo, & Inyang, 2023; Ismail, Wahab, Othman, & Radhan, 2022; Milano, 2016), the authors also utilized new line voltage stability index (BVSI) to obtain the weak transmission lines and was implemented on IEEE 14-bus, 30-bus and 118-bus systems. The proposed model was effective in determining the weakest transmission lines of all the IEEE systems utilized. In (Nkan, Okpo, & Okpura, 2023; Fu, Du, Wang, Zheng, & Xiao, 2023), the authors carried out a comparative analysis of current injection models of the power system network and the power injection models to determine the more efficient model for the voltage stability of the power system. The models were utilized and implemented on a 1479-bus network of island Irish transmission network and it was found that though the power injection model was more complex, it was also more effective in improving the voltage stability of the power system network. (Jameson, Nkan, & Okpo, 2024; Huang, Hill, & Zhang, 2020)in their works, utilized the differences in the voltage source converters (VSCs) which were VSC control loops. The operating states of the device were utilized for the voltage stability of the power system network. The outcome showed that the use of VSC had the expected voltage stability improvement. In (Kettner & Paolone, 2019), studies on the impact of power system structures on the voltage stability disturbances and the weighted load connectivity (WLC) which included an aggregate nonlinear recovery model and network topology characteristics were utilized in determining the voltage stability of the power system network. The monte carlo model was utilized in determining the level of voltage stability of the power system network.

III. MATERIALS AND METHOD

The procedure utilized for the method is shown in the flow diagram of fig.1. Modelled power system network in the power system analysis toolbox (PSAT) is simulated to determine the existing power flow analysis and the level of instability in the power system generation plants situated in the northern region. Optimized placement of FACTS controllers is carried out with particle swarm optimization (PSO) technique by generating the relationship with a high prediction accuracy between voltage at each location and an inter-linked transmission line distance of the 330 kV. The model is generated with least square method and the high prediction accuracy determination is carried out with R-square value of the polynomial order. The best model is optimized and the entire computations are carried out in MatLab. SSSC FACTS controller is implemented on the optimized transmission line and simulated to view the level of steady and dynamic voltage improvement of the system.

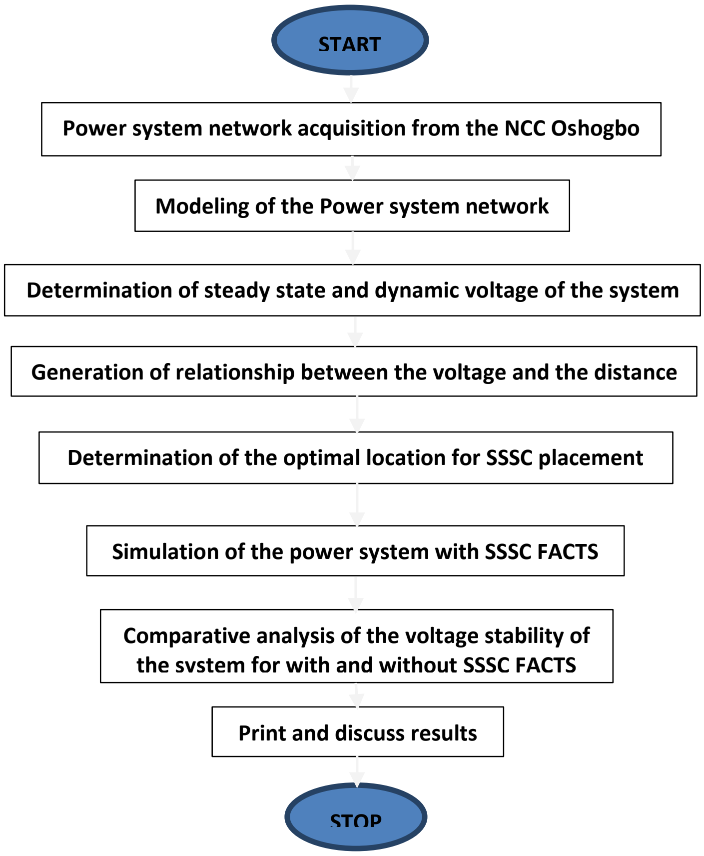

Fig.1. Flow diagram of the research procedure

The study utilized a real time data in the determination of the voltage stability improvement of the power system network. The data is a 32 bus network of the Nigerian 330 kV transmission network. The steady state improvement is on the entire network but the voltage stability is on the generation station of the power system network. The data utilized for the model is obtained from the national control center in Oshogbo, Osun state Nigeria, and the 32 bus network located mainly in the Northern region of the country. The obtained power system network data is simulated in power system analysis toolbox (PSAT) to obtain the steady state and transient stability of the voltage of the network. A polynomial relation between the voltage at each bus and the cumulative voltage of the interconnected network is generated. The polynomial order is increased to achieve the best model with R-square value greater than 95%. The outcome of the model is optimized with particle swarm optimization with the objective function being the polynomial model as shown in Equation 1.

$$P = a_0 + a_1 d + a_2 d^2 + \ldots\ldots + a_n d^n \quad (1)$$

where P is the voltage, a represents the coefficient of the model, d is the distance in km and n is the order of the polynomial. The best order is optimized with PSO in MatLab to determine the distance with the highest active power amount. The FACTS utilized is placed in this location for voltage stability. The essence of utilizing PSO is to determine the optimal location for the placement of SSSC FACTS. The steady state and dynamic voltages of the power system without and with SSSC is compared and presented. The computations are carried out in MatLab and the power system simulation done in PSAT application software.

IV. RESULTS AND DISCUSSION

The steady state voltage of the power system network after simulating the power system network without SSSC FACTS device is shown in Table 1.

Table 1. steady state voltage of the powersystem network

Transmission lines	Voltage (kV)	Cumulative distance
1	320.07	0.47
2	320.53	5.67
3	316.63	315.67
4	320.57	396.67
5	319.16	404.67
6	316.49	648.67
7	317.39	718.67
8	318.73	875.67
9	320.79	908.67
10	320.82	1027.7
11	316.79	1108.7
12	320.85	1210.7
13	320.79	1461.7
14	318.43	1537.7
15	320	1601.7
16	316.71	1622.7
17	318.11	1678.7
18	320.58	1897.7
19	319.96	2079.7
20	320.8	2223.7
21	319.28	2283.7
22	316.18	2513.7
23	320.25	2710.7
24	320.67	2995.7
25	319.39	3260.7
26	319.79	3420.7
27	319.72	3660.7
28	317.96	3920.7
29	319.28	4224.7
30	316.86	4278.7
31	319.53	4374.7
32	316.16	4441.7
33	317.38	4502.7
34	316.23	4584.7
35	316.49	4779.7
36	320.12	4916.7

The best polynomial that was sent to the PSO tool was 7^{th} order polynomial at R-square of 99.61%. The optimal distance obtained from the PSO optimization technique was 236.1kM. The location had the least voltage of 314 kV. Hence, the distance was between Jebba TS and Shiroro GS. Therefore, the FACTS device was placed at the transmission line connecting Jebba transmission station and Shiroro Generating station (line 3 connecting bus 2 and bus 4). The power system model with SSSC FACTS controller is shown in fig.2. SSSC was implemented in the optimized location and simulation of the system was carried out. The steady state voltage of the power system without and with SSSC is shown in fig.3.

From the comparative graph of fig.3, the percentage voltage improvement is 4.3% at the least and the maximum is 5.7%. This simply implies that the introduction of the SSSC FACTS device improved the voltage of the power system networks. The comparative voltage stability with and without SSSC for Geregu GS is shown in fig.4. Here, the oscillations of the voltage for the system without FACTS are high and the introduction of SSSC damped the oscillations by 34.3%. Fig.5 depicts the voltage stability of the Jebba generation station where the oscillations of the power plant was damped to 34.2% with the introduction of the SSSC. Hence, the introduction of the SSSC improved the stability of the power system network.

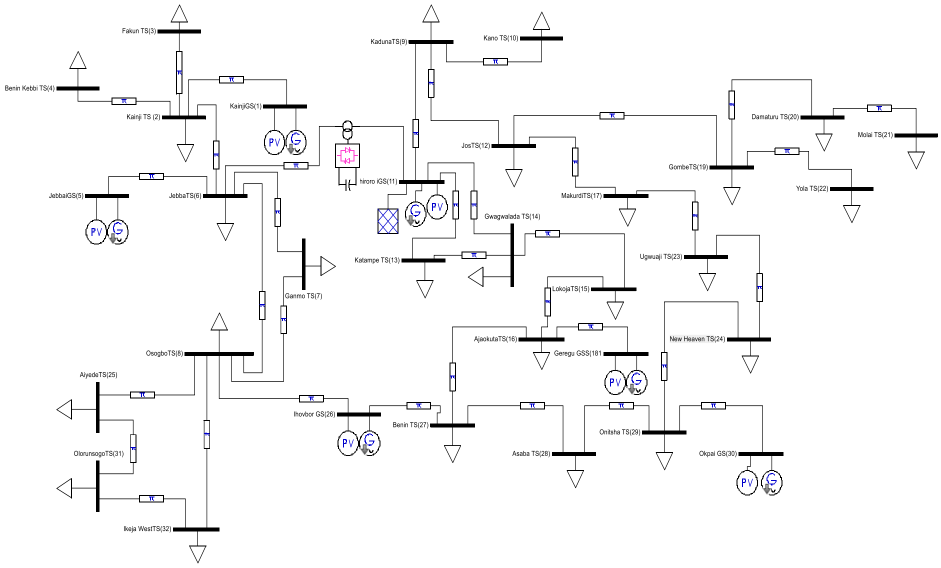

Fig.2. Power system model with SSSC

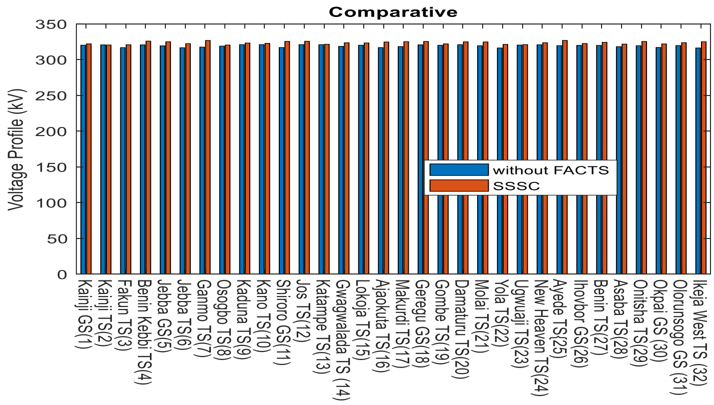

Fig.3. Comparative bar charts of steady state voltage without and with SSSC

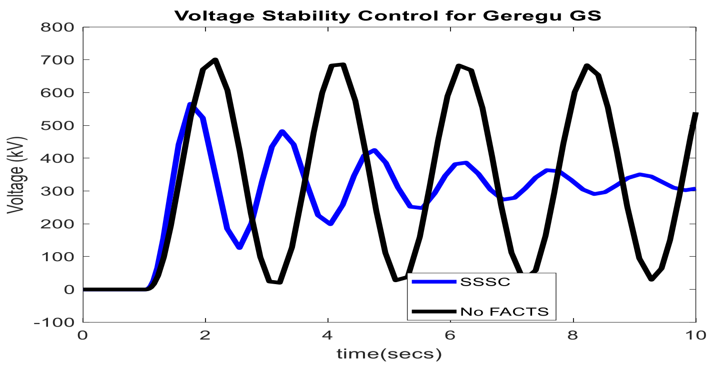

Fig.4. Voltage stability of the Geregu GS

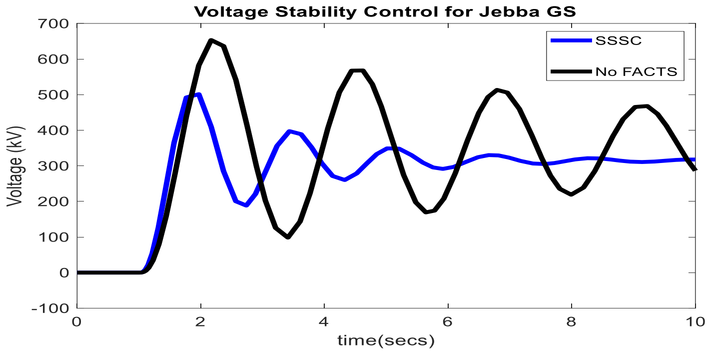

Fig.5. Voltage stability of Jebba GS

V. CONCLUSIONS

The major issue with increase in voltage instability has always been due to the power flow congestion and load imbalance as a result of increase in load demand. Static Synchronous Series Capacitors (SSSC) FACTS device was implemented in this study to improve the voltage stability of the power system network. The power system network was modeled and simulated and the voltage profile was obtained and utilized in generating the polynomial relationship between the voltage and the distance of the interconnected system. An optimal location was obtained when the model was subjected to Particle Swarm Optimization (PSO) technique to determine the optimal location which was on the line connecting Jebba and Shiroro GS buses. With the implementation of SSSC, both steady state voltage and dynamic voltage improvements were recorded.

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