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LARGE SCALE PENETRATION IMPACT OF PMS-WTGs ON VOLTAGE PROFILE AND POWER LOSS FOR 5- BUS, 330kV SYSTEM OF THE NIGERIAN GRID

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Abstract

In recent times, adverse environmental changes and the gradual reduction in fossil fuel deposits is making integration of renewable energy secure global attention. This paper therefore investigates the effect of high penetration of wind power on power loss and voltage profile of 52-bus, 330kV Nigerian grid. Modeling and simulation of the study were successfully done using the Continuation Power Flow method and Power System Analysis Toolbox in the Matrix Laboratory environment. The Ant Colony Optimization (ACO) technique codes were used to determine the best sites and sizes of Permanent Magnet Synchronous-based Wind Turbine Generators (PMS-WTGs) on the grid as non-optimal placement and size of PMS-WTGs will result into active power losses and poor voltage profile. The ACO and power flow analysis indicated two load buses, Aladja bus and Yola bus as best sites for PMS-WTGs with optimal sizes of 100MW and 197MW respectively. The result shows a decrease in the system's active (42.1%) and reactive (43.9%) power losses while heightening voltage magnitudes of critical buses to statutory values and enhancing the grid power quality. The overall results indicate that integrating 297MW PMS-WTGs improves voltage stability and power loss reduction by maximizing system loadability and reducing line losses.

1.0 INTRODUCTION

In recent times, renewable energy (RE) integration is gradually securing global attention as a result of contrary environmental changes and depletion of fossil fuels. Integration of RE can improve power quality by reducing system losses and enhancing voltage profile, meeting the rising global demand for energy and cutting greenhouse gas (GHG) emission [1]. Lately, a huge number of WTGs are being integrated into power grids as wind energy which is the most widely used among the renewable energy resources (RERs). WTGs are either variable speed wind turbine (VSWT) or fixed speed wind turbine (FSWT). VSWT can be grid integrated via permanent magnet synchronous generator (PMSG) or doubly fed induction generator (DFIG) alongside power electronic devices (converters). VSWTs are mostly employed in big wind farms because they can easily adjust reactive power (Q) unlike FSWTs that draw reactive power from the grid network and thus cause decline in power system voltage stability margin [2].

There is greater concentration on the capability of DFIG based wind power plants as seen in current

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studies. But PMS-WTGs also has noteworthy benefits like gearless and simplified drive train structure, high power density, self-excitation system, optimal power extraction ability from wind besides improved grid support ability in the event of any grid disturbance. Above all, the dependability and efficiency of PMS-WTGs are far greater when compared with DFIG-based wind power generators because of the elimination of the gearbox [3]. The continuous rise in demand of electric energy has resulted into an increased stress and faults occurrence on transmission lines. Power flow is primarily restricted by a few characteristics like stability, voltage and thermal limits. Power flows on transmission lines cause electric power loss that introduces heats on the lines. And this causes the transmission line to sag as a result of the aluminum expansion. As the temperature rises higher, the sag gets permanent and finally the aluminum begins to melt and the transmission line breaks . This transmission line failure successively results in voltage instability. The limitations can lead to into an emergent installation of extra transmission lines so as to increase the generation capacity.

High electric power losses, erratic nature of power supply, insufficiency in power generation, old power system infrastructures, and power instability issues constitute a few of Nigerian power grid challenges [6]. The power generating stations are mostly sited in the southern part of the country, where there is sufficient supply of oil and gas. So, long transmission lines have to be used in evacuating the generated electricity to the consumers dwelling in the northern part of the country. And this electricity transmission does not take place without dissipation of much power loses. Also, overvoltage occurs as a result of excessive accumulation of reactive power on the long transmission lines. Electric power losses are wasteful energy dissipated in the power system and are mostly incurred between sources of supply to load centres as electricity consumption is reduced. All of these constitute a "weak" national grid characterized with a very long transmission line carrying a small amount of power. This in turn affects the nation's economy. And so, steps to limit and minimize the losses have to be taken. Consequently, new generators have to be installed near the consumers [7] especially in the Northern region which is very prone to voltage instability due to absence of huge power generators at the moment.

Nevertheless, the accompanying huge extension of gas pipelines from Southern areas where there are abundant sources of energy supply to Northern areas and menace of pipelines vandalization are key limitations to gas-fired power generation in Northern areas of Nigeria. The conventional thermal, gas-fired plant installations in the Northern region would have been, interestingly, the headway to solving the problem of voltage stability, thereby circumventing the afore-mentioned limitations. Hence, there is quest for renewable energy generation and transmission expansion. Fortunately, the huge potentials of wind energy generation in Nigerian northern states like Bauchi, Katsina, Plateau, Kano, and Sokoto could be harnessed for sustainable power quality and development in the country [1] and [8].

Several were done on RERs' integration into national electric grids to enhance power quality issues [9-13,15,17]. Study in [9] gives a decarbonization pathway in the United States and how to satisfy American reduction targets of GHG emission. Authors in [14] give an investigation and impact assessment of solar photovoltaic (SPV) high penetration on static voltage stability and system's loadability of unbalanced distribution system. A probabilistic study to assess grid-connected renewable generation system voltage stability using Active Power–Voltage PV and Reactive Power–Voltage QV curves was done in [15]. Integration of optimally sized SPV and battery energy storage systems impact on voltage stability enhancement and reduction of power loss was considered in [17].

Studies have also been carried out on providing solutions to the problem of power losses in power networks [2], [7, 8, 10]. The study in [2] gives a probabilistic method in assessing impact of a distributed wind turbine generation on a 33-bus radial test system. Effect of solar photovoltaic (SPV) generation on minimization of line losses and improvement of voltage profile of Minna Town 33/11kV distribution network was assessed using Reactive Power–Voltage (PSAT) environment in [10]. Particle Swarm Optimization (PSO) technique was used to optimally placed solar photovoltaic generators (SPVG) in the network but sizing of SPVG was not considered. Improvement of energy loss reduction and voltage profile using capacitor on a distribution system was examined in [7]. The reactive power compensation was aided by the static capacitor and encouraged improvement of voltage in FSWT distributed generation.

Researches have been conducted on impact assessment of wind power integration into power system for voltage stability [15, -17]. The study in [17] is on large-scale impact assessment of grid-connected SPV voltage stability. However, there are not enough researches on RE integration in weak national grids towards system power loss minimization and voltage stability enhancement. This paper therefore proposes optimal sizing and siting of PMS-WTGs for enhancement of voltage profile and power loss minimization of weak power grids.

The remainder of the study is arranged as follow: Modelling of wind generation system is discussed in Section 2.1. Section 2.2 discusses the ant colony optimization technique. Section 2.3 discusses the problem formulation. Section 2.4 elucidates the analysis of the study case system. Section 3.0 provides results and discussion while Section 4.0 gives the conclusion of the work.

2.0 METHODOLOGY

2.1 Modelling of Wind Power Generation System

In this study, power system is made of wind energy, wind turbine, PMSG based wind generators, electronic converter and power system network as shown in Figure 1 which is the overview of PMS-WTGS. The wind turbines capture wind energy via the blades and convert its energy to mechanical energy (torque) that is delivered unto the generator's rotating part. The generator gives out electrical energy, difference in wind turbine's and generator's torques determines whether the system will accelerate or otherwise [4]. The generator is linked to a 3-ϕ, back-to-back converter. The rectifier part rectifies the current and charges DC capacitor. The capacitor feeds inverter side that is connected to Nigerian network, through a step-up transformer.

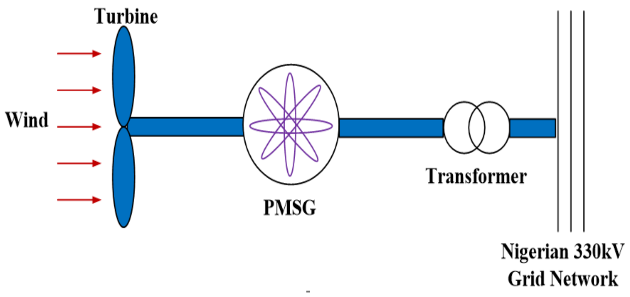

Figure 1: PMS-WTGs Steady-State Model

2.1.1 Modelling of PMSG-Based VSWT

2.1.1.1 Modelling of VSWT

Mechanical input power of wind turbine (P_m), according to Betz's theory of aerodynamics, is [11]:

$$P_m = 0.5\rho A C_p(\lambda, \beta) u^3 \quad (1)$$

where ρ is the air density (kg/m^3), u is the wind speed (m/s), A is rotor blade area (m^2), β is the pitch angle of turbine blade, λ is tip speed ratio, and C_p is coefficient of power. The wind turbine torque is:

$$T_t = \frac{P_m}{\omega_t} = \frac{P_m = 0.5\rho A C_p u^3}{\omega_t} \quad (2)$$

where ω_t is turbine speed.

2.1.1.2 Permanent Magnet Synchronous Generator, PMSG, Model

The wind turbines in this study employ Permanent Magnet Synchronous Generator dynamic model, developed in direct and quadrature (d-q) rotating reference. Their voltage equations can be written as [11]:

$$v_d = -R_s i_d - L_d \frac{di_d}{dt} + \omega L_q i_q \quad (3)$$

$$v_q = -R_s i_q - L_q \frac{di_q}{dt} - \omega L_d i_d + \omega \varphi_f \quad (4)$$

where v_d is direct axis stator voltage, v_q is quadrature axis stator voltage, R_s is the winding resistance of stator, i_d is direct axis stator current and i_q is quadrature axis stator current, ω is angular speed (rad/s), L_d is direct axis stator inductance and L_q is quadrature axis stator inductance, and φ_f is generator flux. The electromagnetic torque of the generator is [4]:

$$T_e = 0.75P\left[\left(L_d - L_q\right) i_d i_q + i_q \varphi_f\right] \quad (5)$$

2.1.2 Power flow calculations

In this study, CPF analysis has been done using Matpower command in MATLAB main coding. Matpower is a freely available programming tool for optimal power flow (OPF) analysis [18]. Matpower is a very good optimization and simulation tool used by several renowned researchers. It runs on MATLAB and its running process comprises three (3) steps depicted in Figure 2 [14]:

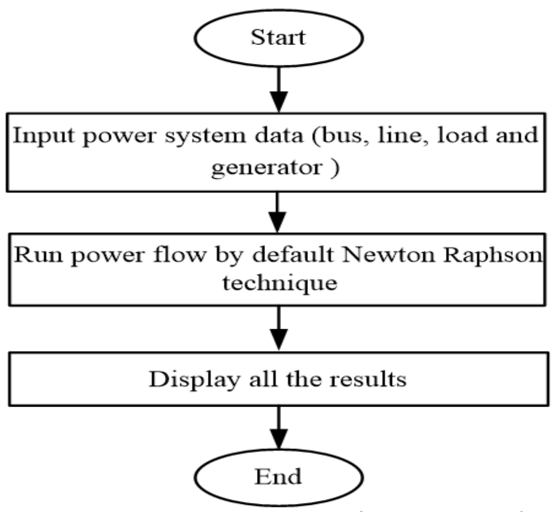

Figure 2: Matpower running process flowchart

Newton - Raphson technique is considered in this study because of its speed of convergence particularly in very large power system networks and its adaptability in most power system modelling software such as MATLAB [16].

Continuation Power Flow (CPF) is a widely-known algorithm applied to evaluate voltage stability of power system using predictor-corrector scheme as depicted in Figure 3. This is an advanced form of NR's power flow solution used in generating PV curve, with gradual load changes. CPF is engaged mainly when the Jacobian matrix of PF expressions turns singular at saddle node bifurcation point (SNBP), point of maximum loading [5].

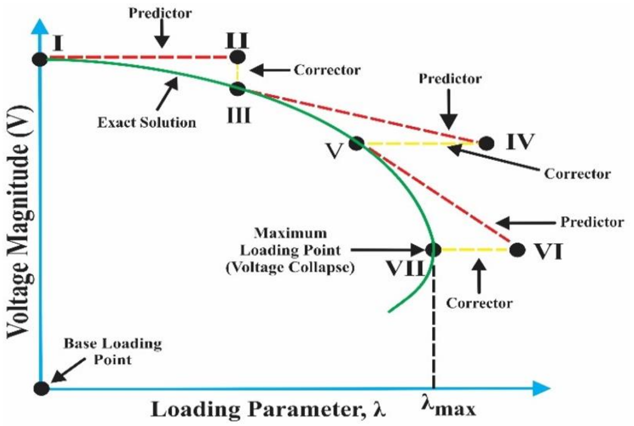

Figure 3: Continuation power flow process [19]

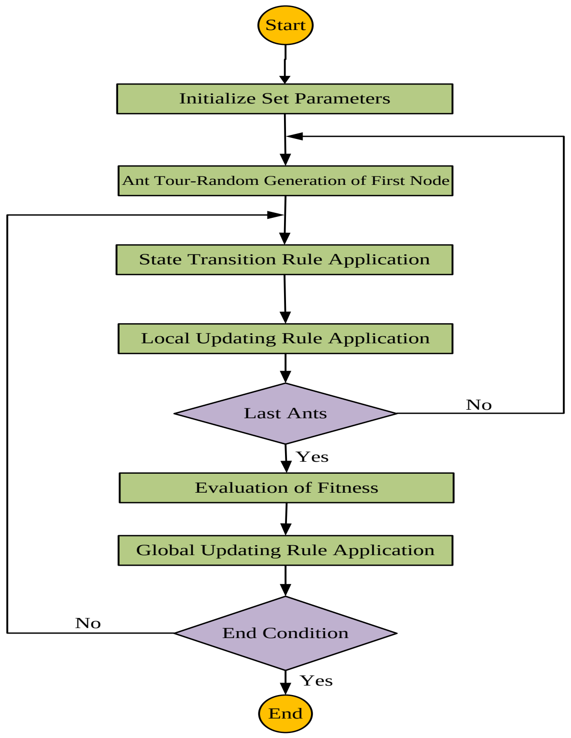

Figure 4: Ant colony optimization flow chart

2.2 Ant Colony Optimization (ACO)

ACO can be likened to simulation of a pack of agents operating collectively to provide solution to optimization problems via an uncomplicated communications. In this study, ACO is engaged to strategically site and size PMS-WTGs due to its reduced search period resulting into faster convergence outcomes as a result of reduction in computation time. Figure 4 is the flow chart of ACO technique [23].

2.3 Formulation of Problem

Since the target in this study is to enhance voltage stability and power loss reduction, the problem formulation requires applying multi-objective functions while ensuring operational equality and inequality constraints. The objective functions are attained as follows:

2.3.1 Minimization of voltage deviations (OF_1)

To ascertain stable system voltage, a better approach is to minimize the voltage deviation (VD). Minimization of VD is expressed as [23]:

$$OF_1 = min(VD_i) = min\left(\sum_{i=1}^{N_{PQ}}(V_i - 1)^2\right) \quad (6)$$

where VD_i is the voltage deviation of i^{th} bus, N_{PQ} is the number of possible PMSG-WGS locations, V_i is voltage at i^{th} bus.

2.3.2 Power loss minimization (OF_2)

OF_2 is expressed as follows [20]:

$$Power\ Losses_{with\ WTG} \leq Power\ Losses_{without\ WTG} \quad (7)$$

$$OF_2 = P_{loss} = min \sum_{i=1}^{n} I^2 R_i \quad (8)$$

$$OF_2 = P_{loss} = min\left(\sum_{i=1}^{n} R_i \frac{P_i^2 + Q_i^2}{V_i^2}\right) \quad (9)$$

n is bus number.

2.3.3 Optimization constraints

2.3.3.1 Equality Constraints

The general form of power flow equation is [16]:

$$P_i = \sum_{k=1}^{n} V_1 V_k Y_{ik} \cos(\delta_i - \delta_k Y_{ik}) \quad (10)$$

$$Q_i = \sum_{k=1}^{n} V_1 V_k Y_{ik} \sin(\delta_i - \delta_k Y_{ik}) \quad (11)$$

where, P_i is i^{th} bus injected active power, Q_i is i^{th} bus reactive power, V_i is i^{th} bus voltage magnitude, δ_i is i^{th} bus angle magnitude, V_k is k^{th} bus voltage magnitude, δ_k is k^{th} bus voltage angle, Y_{ik} is (i, k) element of admittance matrix.

Total power balanced constraint requirements are as given [22]:

$$\sum_{i=1}^{n_{WTG}} P_{WTG} + P_s = \sum_{k=1}^{n_1} P_{losses} + \sum_{i=1}^{n} P_{load} \quad (12)$$

$$\sum_{i=1}^{n_{WTG}} Q_{WTG} + Q_s = \sum_{k=1}^{n_1} Q_{losses} + \sum_{i=1}^{n} Q_{load} \quad (13)$$

where, P_{WTG} is power supplied by PMS-WTGs, P_s is power supply from conventional grid, P_{load} is power supplied to system loads, P_{losses} is Power loss in the network, k is number of wind turbine generators.

2.3.3.2 Inequality Constraints

A. Power injection constraint:

Wind turbine generation operating constraints [21]:

$$\sum_{i=1}^{n} P_{WTG} < P_{load} + P_{losses} \quad (14)$$

$$P_{WTG}^{min} \leq P_{WTG} \leq P_{WTG}^{max} \quad (15)$$

$$Q_{WTG}^{min} \leq Q_{WTG} \leq Q_{WTG}^{max} \quad (16)$$

B. Bus voltage constraints:

The wind turbine voltage constraints [25]:

$$V_i^{min} \leq V_i \leq V_i^{max} \quad (17)$$

$$V_{WTG}^{min} \leq V_{WTG} \leq V_{WTG}^{max} \quad (18)$$

In addition, IEEE 1547 rule presents voltage regulation at all buses to be within the acceptable limit of $\pm 5\%$ of nominal voltage ($0.95 \leq V_i \leq 1.05$).

2.3.4 Multiple objective optimization model

Combined with the stated objective constraint conditions in Equations (10) – (18), the objective functions expressed by Equations (6) – (9) are represented as multi-objective optimization problem given as:

$$\begin{cases} \min f_i(x), & i = 1, 2, 3, \ \dots\ m \\ s.t \begin{cases} g_j(x) = 0, & j = 1, 2, 3, \ \dots\ n \\ h_k(x) \leq 0, & k = 1, 2, 3, \ \dots\ o \end{cases} \end{cases} \quad (19)$$

where, $f = (VD, P_{loss}, -\lambda)$ is target function, $g_j(x)$ and $h_k(x)$ are equality and inequality constraints, x is vector made up of the decision variables.

2.4 Case Study System Analysis

The study case system is 330kV, 52-bus Nigerian grid network. The system has eighteen (18) thermal-hydro generating stations, fifty - two (52) buses, sixty - six (66) transmission lines, transformer and thirty - five (35) static loads. Table 1 gives summary of the study case system attributes.

Table 1: System Summary of Study Case

How many?		How much?	P (MW)	Q (MVAr)
Buses	52	Total Generation Capacity	5167.8	-4904.3 to 6714.7
Generator	18	Online Generation Capacity	5167.8	-4904.3 to 6714.7
Generator (Committed)	18	Actual Generation	3692.8	1272.2
Load (Fixed)	35	Fixed Generation	3658.0	1745.0
Load (Dispatchable)	0	Dispatchable	- 0.0	-0.0
Branch	65	Power Losses	22.741	187.15
Transformer	1	Branch Charging	-	759.4
Inter-tie	0	Total Inter-tie Flow	0.0	0.0
Area	1			

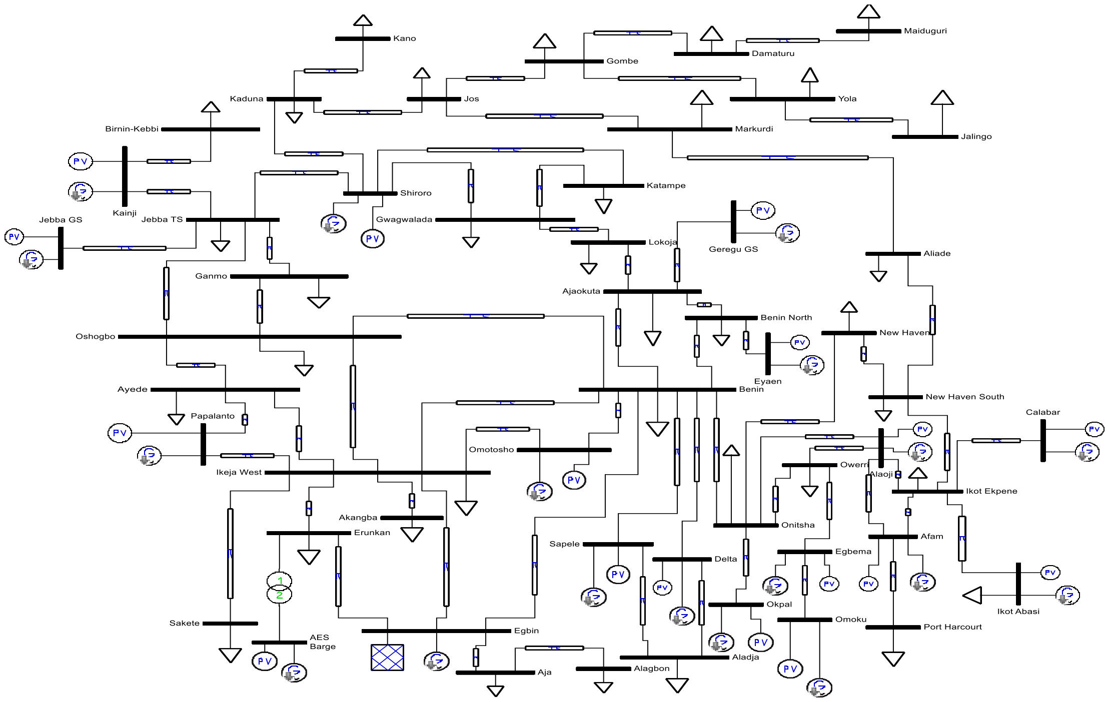

Figure 5: 52-Bus, 330 kV Nigerian Grid Single Line Diagram

The system was modelled using PSAT in MATLAB and presented in Figure 5. The complete data used in the network modelling were gotten from National Control Centre and Transmission Company of Nigeria.

These three cases were investigated during test network analysis:

i. Case 1 - Base case scenario
ii. Case 2 - Effect of PMS-WTGs integration to the network on system power loss
iii. Case 3 - Effect of PMS-WTGs integration to the network on system voltage profile

3.0 RESULTS ANALYSIS

The sole aim of the power flow analysis in this study is to examine system active power loss, reactive power loss and bus voltage profile under high penetration of wind power. The analysis is performed with CPF in Mat-power and PSAT in MATLAB environment.

3.1 Case 1: Base Case Scenario

The data of the study case was used in MATLAB codes to model 52-bus, 330 kV Nigerian power network. The modelled generator active power capacity and load demand are 3692.8MW and 3658.0 MW respectively. The maximum active power loss (I^2R) of 3.914 MW was recorded on Jos – Gombe line. Total active power loss and reactive power loss of the system are 22.741MW and 187.15MVar. Voltage profiles of all network buses are as given in Figure 6.

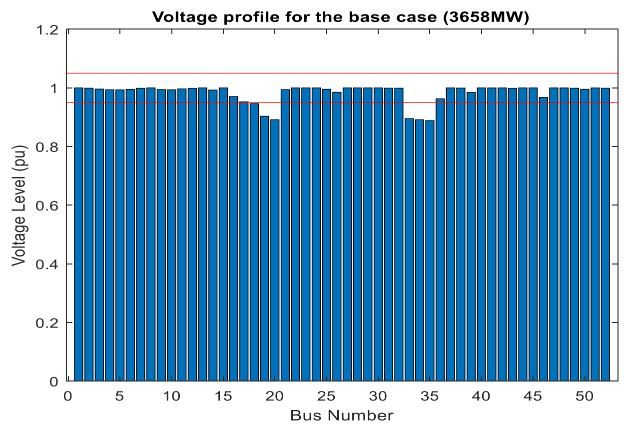

Figure 6: Voltage profile for case one

Voltage profiles of Yola, Gombe, Maiduguri, Jos, Damaturu, and Jalingo buses fell below the lower statutory voltage limit, 0.95p.u. and therefore constitute the critical buses which can throw the network into instability. Among these six buses, the most critical bus is at Jalingo having voltage magnitude of 0.84pu and angle of -20.79 deg. The effect of PMS-WTGs integration on the bus voltage profile and system power loss is then considered on the grid.

3.2 Case 2: Effect of PMS-WTGs Integration to the Grid on System Power Loss

The essence of integrating PMS-WTGs into the grid to investigate the stability of the network is examined in this section. The ACO technique codes were used for optimal siting and sizing of PMS-WTGs on the grid as non-optimal placement and size of PMS-WTGs will result into active power losses and poor voltage profile. The simulation and power flow analysis of the network indicated load buses, Aladja and Yola, as optimal sites for PMS-WTGs with 100 MW and 197 MW capacities respectively. Active power loss and reactive power loss are found to have reduced. Figure 7 depicts the relationship of active power losses before and after integration and ACO of PMS-WTGs. The total active and reactive power loss reduction of 42.1% (from 22.741 to 13.170 MW) and 43.9% (from 187.15 to 104.96) were observed.

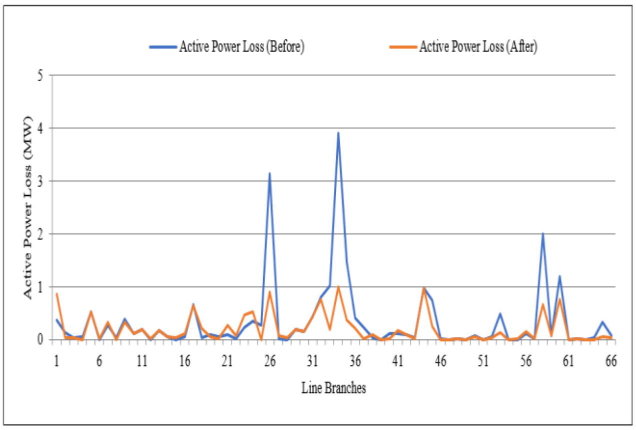

Figure 7: Active power losses before and after integration of PMS-WTGs to the grid

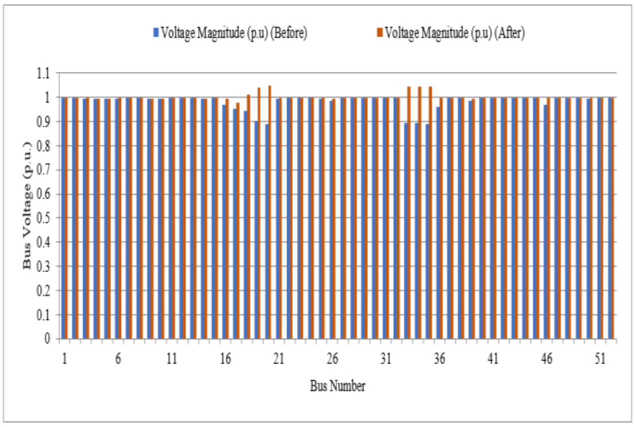

Figure 8: Voltage fluctuations before and after wind integration and ACO

3.3 Case 3: Effect of PMS-WTGs Integration to the Grid on System Voltage Profile

The system voltage profile also improves and system becomes more stable. With continuous increase in wind power until the optimal size of 297 MW is achieved, voltage profiles of the buses particularly the critical buses improve. Figure 8 which represent voltage profiles of 52-bus, 330 kV Nigerian network before/after the integration and optimization of WTGs. Immediately that optimal size is exceeded; two of the critical buses (Gombe and Maiduguri) had their voltage profiles rise slightly higher above the upper bus voltage statutory limit, 1.05pu. This then implies that the study case network can only handle as much as 297 MW wind power integration.

4.0 CONCLUSION

In this work, impact of integrating wind power into a grid for system power losses and voltage profile improvement has been examined. Continuation power flow analysis in Matpower and Ant Colony Optimization technique were used. The optimization, Matpower simulation and power flow analysis of the network reveal Aladja bus and Yola bus as optimal sites for PMS-WTGs. The active power loss shows a great reduction and voltage profiles especially of the critical buses show significant improvement. In the final analysis, results demonstrated an improvement in voltage profile, active power and reactive power losses reduction, thereby palliating occurrence of system collapse. Therefore, wind power can be harnessed to address the power quality challenges of weak grids especially in Northern states of the country and also ease her increasing energy demand.

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