Integration of Wind Power to the University of Lagos Electrical Distribution System

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ABSTRACT

The feasibility and prospect of integrating wind energy into the existing distribution system of the University of Lagos (UNILAG) is explored in this work. The main source of UNILAG's electricity supply is the national grid which often fails. When this happens, the university owned generators are used to provide electricity to some parts and this is done at a high financial cost, with the attendant noise and air pollution. The system was first analyzed with a view to determining the level of wind energy that can be integrated to complement the power supplied by the existing diesel generators. The wind-integrated network was then simulated to determine the permissible operating region that complies with the voltage stability limit at the point of common coupling (PCC). MATLAB was used for load flow analysis and simulation. Results show that ten turbines or less would ensure a stable operation of the system and supply the required power.

Key words: UNILAG, wind energy, integration, network, PCC

1 INTRODUCTION

It is now common to find renewable energy resources, especially wind power, connected to distribution systems. Wind energy is basically the fastest growing electrical energy producing technology in the world today and is among the cheapest renewable energy sources per unit of electricity produced. The prospects of wind energy in Nigeria are quite good with wind speeds ranging from 1.4 - 5.12 m/s [1].

UNILAG is one of the universities in the south west of Nigeria and its main campus is bordered mainly by the Lagos lagoon and has prospects for a small onshore or offshore wind farm for electricity generation. The running cost of wind turbines is negligible [2]when compared with the running cost of diesel generators presently being used; therefore the development and utilization of electrical energy from wind will reduce UNILAG's overdependence on the presently unreliable power supply from the grid. It would also ensure longer life spans for the supporting generating sets and would reduce CO2 emissions and adverse effects on residents and the consequent global warming. Also, excess power generated could be sold to nearby small scale industries with financial returns. Faculties of Engineering and Science, in particular, would largely benefit from installation of a wind farm since laboratory sessions can go on interrupted. There is also the opportunity of training students in the current trend which emphasizes the use of renewable energy technologies.

The overall purpose of a power system is to meet electrical energy needs of consumers in the best way possible, technically, economically and socially. Wind energy introduces power quality issues when integrated into an existing grid due to the peculiar characteristics of wind energy. This is particularly so when contribution of wind energy to the grid is substantial.

Transmission systems, used by existing conventional generations, are often not designed to accommodate large-scale wind energy or are simply not available near existing transmission networks. Grid connection challenges also include economic issues such as, cost for offshore wind power connection, long permission procedures, low capacity factor of transmission systems for wind power [3] and legal issues [4] [5]. As a result of wind power connection, transmission bottlenecks may occur, which may be solved in a number of ways, including grid reinforcement or phase shifting transformers [6], wind energy curtailment, or even local storage [7]. Also, to cope with large wind power penetration levels, an increasing number of countries are adopting grid codes with requirements for wind turbines. The objective of this is to manage the impacts that wind power may have on existing power systems. Since the grid code requirements for wind power are implemented on a national scale, a wide range of technical requirements now exists between countries [8]. These integration issues associated with large wind farms also bring gives extra weight to the advantages of private or autonomous wind farms such as is proposed for UNILAG. Also, some modern wind turbines are capable of fulfilling strict grid-code requirements, for reliable power system operation just like conventional generation technologies [9].

2 Analysis of UNILAG Power System

2.1 Overview

The UNILAG power network is an eight-feeder distribution system depicted in Fig. 1; the portion marked with dashed line is the system without wind integration.

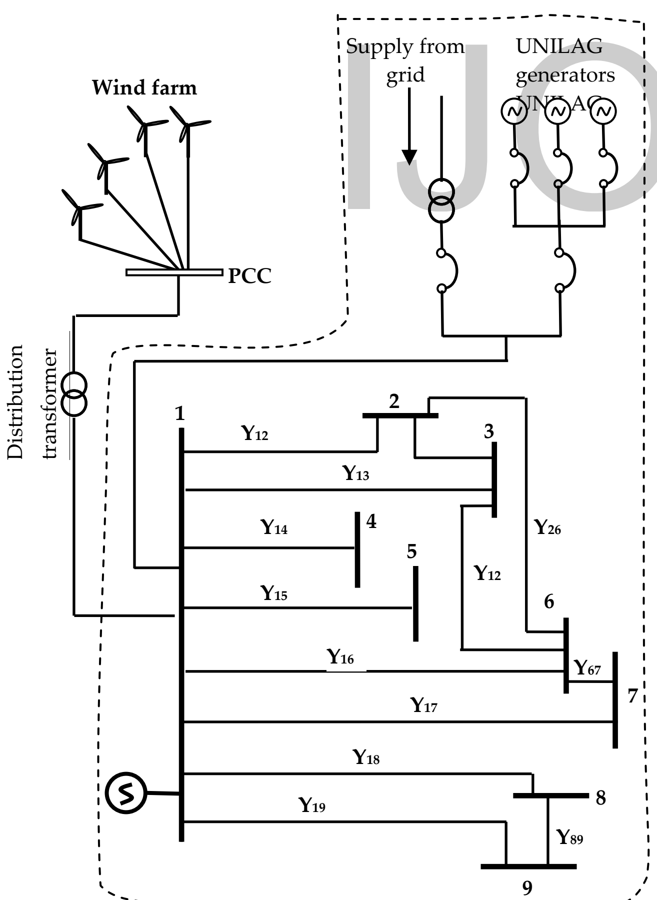

Fig. 1: Wind turbines integrated in existing UNILAG grid.

The generation stage consists of the incomer and three diesel generators; each supply works independently. When there is no supply from the grid, the generators supply most of the required energy, and when supply from the national grid is restored the generators are shut down. Load flow analysis of the system was carried out using Gauss-Seidel method. Bus 1 is taken as the slack bus. Buses 2 to 9 are the load buses. V_1 is the voltage at the slack bus while V_2 to V_9 are the voltages buses 2 to 9 respectively.

$$V_2^{(k+1)} = \frac{\dfrac{P_2^{sch} + jQ_2^{sch}}{V_2^{*(k)}} + Y_{21}V_1 + Y_{23}V_3^{(k)} + Y_{26}V_6^{(k)}}{Y_{21} + Y_{23} + Y_{26}} \quad (1)$$

$$V_3^{(k+1)} = \frac{\dfrac{P_3^{sch} + jQ_3^{sch}}{V_3^{*(k)}} + Y_{31}V_1 + Y_{32}V_3^{(k)} + Y_{36}V_6^{(k)}}{Y_{31} + Y_{32} + Y_{36}} \quad (2)$$

$$V_4^{(k+1)} = \frac{\dfrac{P_4^{sch} + jQ_4^{sch}}{V_4^{*(k)}} + Y_{41}V_1 + Y_{45}V_5^{(k)}}{Y_{41} + Y_{45}} \quad (3)$$

$$V_5^{(k+1)} = \frac{\dfrac{P_5^{sch} + jQ_5^{sch}}{V_5^{*(k)}} + Y_{51}V_1 + Y_{54}V_4^{(k)}}{Y_{51} + Y_{54}} \quad (4)$$

$$V_6^{(k+1)} = \frac{\dfrac{P_6^{sch} + jQ_6^{sch}}{V_6^{*(k)}} + Y_{61}V_1 + Y_{62}V_2^{(k)} + Y_{63}V_3^{(k)} + Y_{67}V_7^{(k)}}{Y_{61} + Y_{62} + Y_{63} + Y_{67}} \quad (5)$$

$$V_7^{(k+1)} = \frac{\dfrac{P_7^{sch} + jQ_7^{sch}}{V_7^{*(k)}} + Y_{71}V_1 + Y_{76}V_6^{(k)}}{Y_{71} + Y_{76}} \quad (6)$$

$$V_8^{(k+1)} = \frac{\dfrac{P_8^{sch} + jQ_8^{sch}}{V_8^{*(k)}} + Y_{81}V_1 + Y_{89}V_9^{(k)}}{Y_{81} + Y_{89}} \quad (7)$$

$$V_9^{(k+1)} = \frac{\dfrac{P_9^{sch} + jQ_9^{sch}}{V_9^{*(k)}} + Y_{91}V_1 + Y_{98}V_8^{(k)}}{Y_{91} + Y_{98}} \quad (8)$$

An initial voltage estimate of 1.0 + j0.0 was chosen for each unknown voltage, which is satisfactory [14]. All impedances were converted to per unit values after the measurements and calculations. Applying Kirchhoff's Current Law (KCL) to the network and simplifying, gives the following voltages at buses 2 to 9 for k = 0,1,2,...,n which are solved iteratively.

With the final values of all the load bus voltages known, the slack bus power is obtained from (9). Computation of line currents, line flows and line losses were also carried out.

$$P_1 + jQ_1 = V_1^* [V_1(Y_{12} + Y_{13} + Y_{14} + Y_{15} + Y_{16} + Y_{17} + Y_{18} + Y_{19}) - (V_2 Y_{12} + V_3 Y_{13} + V_4 Y_{14} + V_5 Y_{15} + V_6 Y_{16} + V_7 Y_{17} + V_8 Y_{18} + V_8 Y_{18})] \quad (9)$$

With the final values of all the load bus voltages known, the slack bus power is obtained from (9).

2.2 Computer Power Flow Program

The following programs for Gauss-Seidel method obtained from [15] were used in the analysis and are explained briefly:

lfgauss is a program that obtains the power flow solution by the Gauss-Seidel method and requires files named **busdata** and **lfybus.**

lfybus forms the admittance matrix using the line and transformer parameters, and transformer tap settings specified in the input file named **linedata.**

busout produces the bus output result in a tabulated form. The bus output result includes the voltage magnitude and angle, real and reactive power of generators and loads, and the shunt capacitor/reactor MVAR. Total generation and total load are also included as outline in the sample case.

lineflow is a program that prepares the line output data. This displays the active and reactive power flow entering the line terminals and line losses as well as the net power at each bus. The total real and reactive losses in the system are also displayed [14].

2.3 Determination of Line Parameters of the Network

The cable sizes and termination points are depicted in Fig. 2. Several measurements were carried out on the network to obtain cable sizes and lengths because the line data was not readily available. The cable sizes and lengths are shown in the block diagram (Fig. 2) and involve:

- 150mm2 cables from substation (bus 1) to the primary windings of all the step down transformers.
- 70mm2 cables from the secondary windings of the transformers to the main switchboards.
- Between 35-16mm2 cables from main switchboards to the distribution boards.
- Between 10-1.5mm2 cables from the distribution boards to the loads.

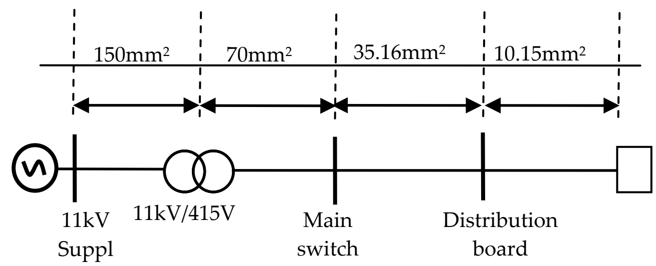

Fig 2: Schematic of cable sizes and connections in the network.

The impedances of the cables according to their sizes and lengths were determined using the Power/Control Cables BS6883 Datasheet for impedance specifications. The per unit impedances were computed on a base of 100 MVA, The 15mm² is on a base voltage V_B of 11kV while other sizes (70 – 1.5mm²) are on a base of 415V. The base impdance was computed using (10); the calculated impedances were used in the load flow analysis and simulation.

$$Z_B = {(V_B)^2}/{S_B} \quad (10)$$

The base impedances for the two categories of cables are

$$Z_{B(150mm^2)} = {(11kV)^2}/{100MVA} = 1.2100\Omega$$

$$Z_{B(70-1.5mm^2)} = {(0.415kV)^2}/{100MVA} = 1.7223x10^{-3}\Omega$$

The load flow results

Results from the load flow analysis showed that the total power generated is (6.100+j0.080) MVA, the total power delivered is (5.778+j4.326) MVA and total power loss along the lines is (0.322+j0.123) MVA.

3 Integration of Wind Power

Wind farms are equipped with wind turbines coupled to generators with which energy from the wind is converted to mechanical power and then to electric power. Different methodologies exist for the development of wind power from wind speed data and include the use of wind turbine power curves, aggregated wind park power curves and statistical modeling [10]. Power curves for the conversion of wind speed to wind power are commonly used for the transformation of measured and synthetic wind speed data-series [11] [14]. Drawback of using a wind turbine power curve for the estimation of an entire wind park is that it over-estimates wind power variations near cut-out wind speeds, especially offshore where there are substantial distances between wind turbines. A methodology for the development of wide-area, aggregated wind park power curves is presented in [13], which allows the development of wind power data based on locational parts of the whole capacity covering large geographical areas. This approach does not allow for the development of wind power data for separate locations.

The wind turbine model provides a simplified representation of a very complex electro-mechanical system including the control system and mechanical dynamics of the wind turbine. The model accepts the machine terminal active power from the wind turbine generator (WTG). The turbine control is designed to deliver power over a range of wind conditions, taking advantage of the variable speed capability of the machine.

The varying wind speed and induction generators generally call for special considerations concerning grid connection and integration into the whole power system. The deterministic approach which makes use of extreme values is a simple method for calculating the steady-state voltage change by wind turbines. Only the maximum voltage change at the interconnection point called point of common coupling or connection (PCC) between the grid and wind farm is calculated. If the output from a distributed wind turbine generator is absorbed locally by an adjacent load the effect on the distribution network voltage and losses is likely to be beneficial. However, if it is necessary to transport the power through the distribution network the increased losses may occur and slow voltage variations may become excessive [15].

Grid connection of a wind farm is shown in Fig. 3, where the impedance Z represents loads, all transmission lines, cables, and transformers feeding the grid. Assuming the active and reactive power production P, Q at the wind farm are known, and the network parameters are known, then the voltage at the supply point, E_s is given in (11).

$$E_s = V_s + (R + jX)I$$

or (11)

$$E_s = V_s + ZI$$

where V is the voltage at any point under consideration

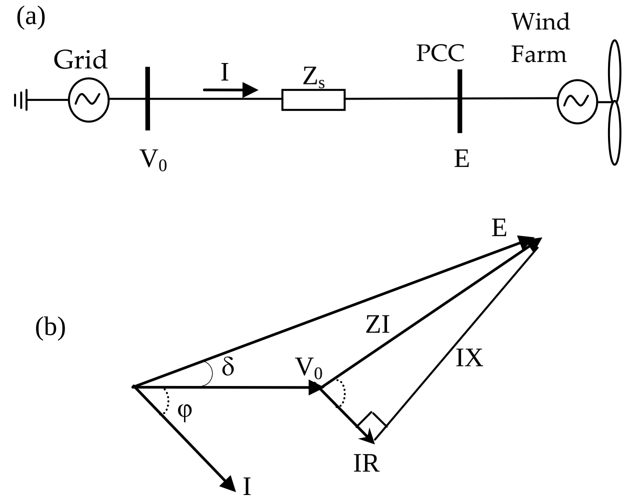

Fig. 3: Grid connection of a wind farm
(a) Equivalent circuit (b) phasor diagram

3.1 Interaction of UNILAG Distribution Network With Wind Farm

A wind farm can be simplified as parallel turbines. In the analysis of the UNILAG electrical system integrated with wind energy, the following assumptions were made:

- The wind turbines are identical.
- Wind speeds at the wind farm are uniform so that all the wind turbines start at the same time.
- Each turbine runs at the same operating condition at all times, thus the voltage current and power factor of the turbines are identical.
- The impedances of the line feeder between each turbine and the PCC are identical and negligible.

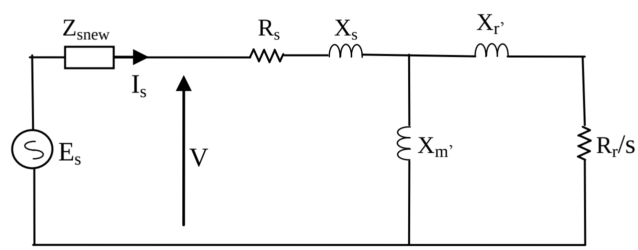

Fig. 4: Induction machine in per-phase, per-turbine analysis

A cluster of wind turbines feeding the UNILAG system is shown in Fig. 1. Each wind turbine is the constant-frequency, induction generator type and each generator is connected to a distribution transformer at the base of the wind turbine. The output from each wind turbine is connected to the PCC from where the output is connected to UNILAG 11-kV busbar through a distribution transformer. The impedances of the transformers and lines are lumped together and represented as Z_S.

The equivalent circuit of an induction machine in per-phase, per turbine analysis is as shown in Fig. 4. With only a single turbine operating, the terminal voltage at the point of common coupling can be expressed as:

$$V = E_s - Z_s I_1 \quad (12)$$

If there are *n* identical turbines operating in parallel, the voltage equation is expressed as:

$$V = E_s - Z_s (I_1 + I_2 + I_3 + \ldots + I_n) \quad (13)$$

With the assumption presented (13), the currents in all branches are equal, that is:

$$I_1 = I_2 = I_3 = \ldots = I_n \quad (14)$$

Equation (14) can be rewritten as:

$$V = E_s - Z_s(nI_1) \quad (15)$$

Or, if analyzed on a per-turbine basis, the equation becomes:

$$V = E_s - (Z_s n) I_1 \quad (16)$$

And the final solution is simplified as:

$$V = E_s - Z_{sNEW} I_1 \quad (17)$$

where $Z_{snew} = nZ_s$

Conducting this analysis on a per-turbine, per-phase basis aids the understanding of collective effects of wind power generation in a wind farm environment. Equation (15) shows that when more wind turbines are added to the wind farm the line impedance increased to a new value, Z_{snew} and therefore characteristics of individual induction generators will change which in turn affects the voltage profile of the system. Required Wind turbine Capacity for Integration

The total average load consumption of the University of Lagos power system is 6MW. This power is supplied at the slack bus of Fig. 1 from where it is distributed through the 8-feeder ring system of the university. The capacity of wind energy to be integrated into this grid should sufficiently supply this load. These wind turbines can be fed into the grid either through the slack or load buses.

The wind turbines manufactured now range from 2 - 3MW and a wind farm can contain different ratings but for the purpose of this analysis, the same rating of turbines is used. If the 2-MW rating is chosen, 4 would be needed to supply the whole load. But more turbines can be installed with a view to exporting the excess power to the nearby companies around UNILAG for extra income. The simulation results in section IV show that the system can conveniently accommodate as many as 10 turbines.

3.2 Output Result for Wind Integration

Different numbers of wind turbines were connected to the existing UNILAG 11kV network by simulation with MATLAB using results generated from the Gauss-Seidel power flow analysis. The parameters of the network were incorporated into (17) based on Fig. 5. Wind energy loading effect on UNILAG distribution network is illustrated in Fig. 6. The impact of varying the slip of the induction generator and the impact of adding more turbines to the same network using normalized voltage at PCC are also shown.

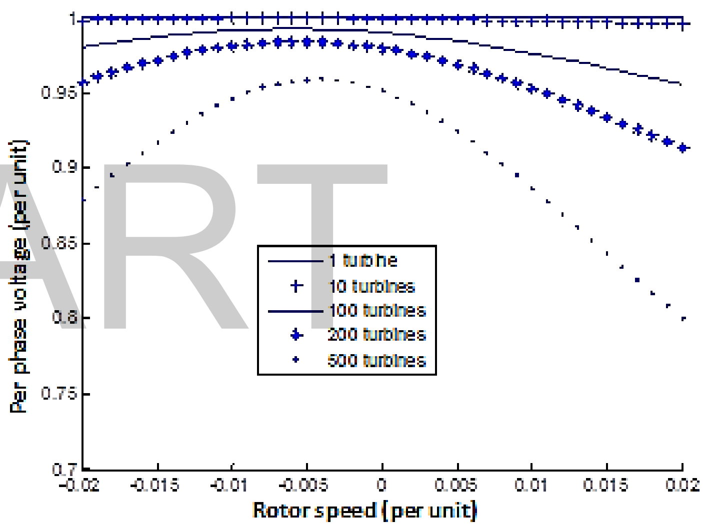

Fig. 5: Loading effect of wind energy on voltage at PCC

With 10 turbines or less, it is obvious that the power system voltage is almost constant with change in slip. In the normal speed range between 0% slip and 2% slip, the voltage variation at PCC is very small (about 1%). However, when the number of turbines is increased to 200 and 500 for instance, the voltage variation becomes larger and drops by as much as 15% for the same operating range.

3.3 Reactive Power Compensation

The steady-state voltage deviations can be kept within acceptable limits by controlling the reactive power flow. Voltage profile at PCC and the stability of the induction generator can be analyzed for different types of capacitor compensation. For the purpose of this research, parallel capacitor compensation was investigated. Parallel compensation relies on the reactive power generated by capacitors in parallel with the induction generator. For a fixed parallel capacitor, the reactive power output of the capacitor is proportional to the square of the voltage across the capacitor. The reactive power required by the induction machines varies with the operating slip. In some wind turbines more than one value of capacitor are used at their terminals for different wind speeds. Reactive power compensation improves voltage regulation of the system. The per-phase, per-turbine compensation using a parallel capacitor at each turbine is illustrated in Fig. 6.

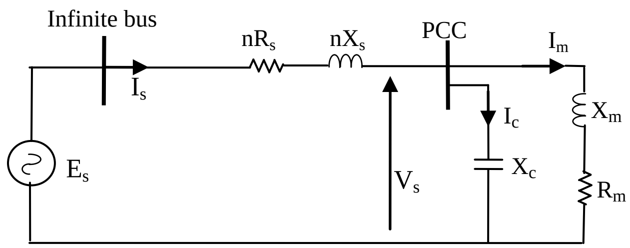

Fig. 6: Capacitor compensation

The total current, I_S is the sum of the wind turbine current I_m and the capacitor current I_C. Based on the equivalent circuit in Fig. 6, the voltage and current equations are:

$$E_s = V_s n(R_s + jX_s)I_s \quad (18)$$

$$I_s = I_m + I_c \quad (19)$$

4 CONCLUSION

The viability of wind power integrated UNILAG distribution system has been investigated and focus has been on voltage stability of the system at different rotor speeds which is by extension, the wind speed. Since increasing the number of wind turbines leads to excessive voltage drop at the PCC, it is therefore recommended that the magnitude of wind energy be restricted to that which the system can comfortably accommodate. Also, capacitor compensation is also necessary to boost the voltage at the PCC, thus improving the rotor speed capability of each induction generator.

It is expected that the success of this autonomous wind farm on a university campus would encourage other universities and corporations in Nigeria to invest in wind farms. This would save substantial revenue currently being spent on fossil fuel to run private generators.

Also worthy of note is that, since the proposed wind farm project for UNILAG is intended be localized, it will not subject to most of the integration issues associated with big wind farms integrated into the general grid. Also, as a private wind farm, power would be generated near load centres, which reduces transmission voltage drop. In addition, less effort is required to distribute load on the system and monitor voltage levels of the generated power supplied to the end users.

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