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Reactive power producing capability of wind turbine systems with IGBT power electronics converters

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ABSTRACT
As a result of the growing wind power penetration especially of Type-1 and Type-2 wind turbine technology that requires reactive power from the electricity grid rather than producing reactive power and with the current trend in the infrastructure of functional wind power plants in nowadays electric-power systems, the aggregate reactive power differences obtainable for nearly all of the

active power functioning points exceeds the reactive power needed by grid code conditions. meaning that, additional services support which is at present provided mostly by traditional generation such as reactive power production need to equally be satisfactory provided by wind power generation in a dependable way. Several requirements for Wind Turbine Generators (WTGs) have been recommended in grid codes. In maintaining with grid codes, WTGs ought to have the possibility of producing reactive power at the Point of Common Coupling (PCC). Hence, the need to take into consideration systematic utilization of existing facilities such as up-grading of existing wind farms to Type-3, Type-4 and Type-5 wind turbine based wind farms owing to their capability to produce reactive power, the Type-4 wind turbine is to a greater extent precisely more appealing as it provides a great deal of pliability in design and operation. This has been explicitly illustrated using a simulation model in MATLAB/Simulink environment; the model consists of renewable wind power source with Insulated Gate Bipolar Transistor (IGBT) power electronics converters installed at the beginning of an electricity distribution line. The computer model produced vividly shows that the wind power source has the ability of producing reactive power in an electricity distribution system. This is a novel way of providing reactive power support according to the increasingly strict requirements of grid codes.

Keywords: wind turbine systems; up-graded wind turbine systems; wind turbine generators; insulated-gate bipolar transistor; reactive power production; electric-power grid.

1. INTRODUCTION

Electricity production from renewable energy sources, such as wind, is growingly drawing attraction due to environmental issues, long-term economic advantages and scarcity of conventional energy sources in the near future. The main cost-efficient and practicable disadvantage of wind power is its intermittent characteristics. Wind power requires not only that wind is flowing, all the same it also rely on cut-in and cut-out wind speed that is the wind speeds at which production starts and is brought to a stop in order to keep away from harm. The production of power from the wind on a large-scale has become an accepted business. It holds substantial prospect for the future, hoping that wind power will become the most accepted choice and form of renewable energy source. Wind energy technology application has come of age, with numerous nations preparing and establishing extensive wind energy farms, with enormous amount of wind turbines. The strength of wind power technology is that it is clean and inexpensive. As a result of increasing fossil fuel price and state-of-the-art technology, more and more residential and commercial consumers of electricity have been installing wind turbines, the motivation being to cut energy bills and carbon dioxide emissions, and are even vending extra electricity back to the grid network. Another motivation is to adopt a policy for independent electricity production, the aim of this policy is to encourage the involvement of independent power producers in the growth and expansion of environmentally sound and inexpensive electricity supply for end-users while adhering to the robustness of the existing electric-power network [1] – [14]. Wind power is one of the rapidly expanding clean renewable energy resource. Currently, plenty of wind farms have been established in several nations from the thought of global warming and exhaustion of fossil fuels. Huge amount of established renewable electric-power resource is wind generated. Established wind farms are anticipated to expand with time coinciding with reduction in the price of wind power technology [15] - [16]. Also, in the same vein nations are now going away from fossil-nuclear age and preparing the way for photovoltaics (PV) in order to contribute a notable part in a future shaped by sustainable energy generation. [17] – [19].

Reactive power is necessary to provide the magnetizing field required by motors and other inductive loads to perform their desired functions. Reactive power can also be interpreted as wattless, magnetizing or wasted power and it represents an extra burden on the electricity supply system and on consumer's bill. An inductive load requires a magnetic field to operate and in creating such a magnetic field causes the current to be out of phase with the voltage that is current lags voltage. There is need for reactive power production of the lagging current by creating a leading current by way of connecting sufficient capacitors to the supply. Inductive loads can be used to keep reactive power low by consumption of more electrical energy. This is so since an inductive load draws reactive power as well as active power. Reactive component is watt less power drawn from the source. We use only active part of the source. It is of benefit to note here that there is no bidding activity for reactive power, electricity end-users do ask for active power but they have to pay for reactive power as well, likewise, electric-power producers provide active and reactive power at a single price but they do bid only for active power and are paid for reactive power as well. Low reactive power also affects other systems in the circuit virtually making cables under sized by heating them. Lagging Kvars due to the prevalence of large inductive loads has the negative effect of increased energy cost, due to penalties imposed by utility authorities, higher system losses, due to reactive power losses and lower utilization power due to the previously mentioned losses. There are several methods available today to attempt to offset the lagging Kvars imposed by inductive power loads. The two most common methods for producing reactive power is the use of shunt capacitors or synchronous motors. Reactive power production can also be provided by locating wind turbines at remote locations, this is the focus of this research work. [20] - [21].

Originally, wind energy did not have any important influence on energy network regulation, but now due to its proportion, wind energy has to perform a substantial more functional role in electric-power grid performance and control. The device utilized in wind turbines was initially established on squirrel-cage induction generator connected exactly to the electric-power grid. Power pulsating nature in wind energy systems were nearly straight away conveyed to the electrical grid by utilizing squirrel-cage induction generator as its speed is fixed owing to its restricted slip limit. Moreover, no dynamic control of the active and reactive power occurred excepting for not many capacitor banks which assured unity power factor at the point of common coupling (PCC). As the energy ability of wind turbines expands, controlling the frequency and the voltage in the electric-power grid happen to be more important, and in then recent paste it has come to be essential to advance power electronics, like Insulated-Gate Bipolar Transistor - Flexible Alternating Current Transmission System (IGBT-FACTS) devices as a brilliant interface connecting the wind turbine system and the electric-power grid. IGBT-FACTS Power electronics devices is altering the fundamental attributes of wind turbines from actually a power source to essentially a reactive power source for the electric-power grid. Owing to the devices utilized in wind turbines, the cost per kW of recently developed wind energy plant is now commensurate and indeed lower than traditional energy systems; consequently, applications with IGBT power electronics devices are extremely appealing [10], [11], [24] - [31].

The rest of this article is organized as follows. Section 2 discusses the rationale for this research work. Section 3explains the structure of the Insulated Gate Bipolar Transistor (IGBT).Section 4 summarizes the materials and methods. Section 5analyses and discusses the computer model results while, Section 6 concludes the article.

2. THE RATIONAL FOR THIS STUDY

Increment in wind power spread of electric-power systems means that, auxiliary services support which is at the present time made available predominantly by traditional techniques such as reactive power production must equally be acceptably provided by wind power generation in a trustworthy manner. The growing wind penetration most especially of Type-1 and Type-2 wind turbine machinery that requires reactive power from the electricity grid as contrasted with generating such, unfavorably influence the voltage stability that has since long been the reason of various notable electricity blackouts observed all over the globe. The Type-1 wind turbine generator is realized with a Squirrel-Cage Induction Generator (SCIG) and it is attached exactly to a step-up transformer. The wind turbine speed is fixed or closely fixed to the electricity grid's frequency, and produces real power when the wind turbine shaft rotates faster than the electricity grid frequency, thereby giving rise to a negative slip, it should be noted here that positive slip and power is motoring custom. While inType-2 wind turbine generators, the wound rotor induction generators are joined precisely to the wind turbine generators step-up transformer in a manner much the same as to that of Type-1 wind turbines with regards to the machines stator circuit, but it equally includes a variable resistor in the rotor circuit [32], [33] - [39].

Wind power turbines specifically fixed speed class with traditional induction generators, exhibit healthy coupling between active power production and reactive power assimilation. Thus, in such type of wind turbine generators, a bit of variation in active power production brings about a corresponding response in reactive power assimilation. In such circumstances, lack of enough dynamic reactive power can exert influence on the system voltage seriously, most seriously near the PCC. In addition to this, lack of sufficient dynamic reactive power provision from wind generators worsen the difficult situation of dynamic voltage reliability in large-scale wind combined power systems. Therefore, in order to ensure stable and secure function of high wind penetrated electricity power systems, optional actions to fortify the voltage reliability is required to be considered. Current wind turbine generators particularly those joined at electricity systems voltage alignment points equally supply a fascinating possibility for dynamic reactive power sustenance, with Type-3, Type-4 and Type-5 wind turbine generators being the principal challengers. This is as a result of their superior control flexibility and the ability to provide reactive power sustenance even during shutdown time. The Type-3 wind power turbine, often referred to as the Doubly Fed Induction Generator (DFIG) or Doubly Fed Asynchronous Generator (DFAG), is an improvement of the Type-2 wind turbine design, by putting in variable frequency Alternating Current (AC) excitation as a replacement of merely the resistance to the rotor circuit. The Type-4 wind power turbine proffers a considerable deal of flexibility in design and operation as the output produced by this rotating machine is sent to the electricity grid by means of a full-scale back-to-back frequency converter. While the Type-5 wind power turbines are made up of a normal wind turbine generator variable-speed drive train joined to a torque/speed converter that is coupled with a synchronous generator [33] - [39].

With appropriate up-grading of existing Wind Power Plants (WPPs) built at possible locations that are vital for dynamic voltage control, notable large amount of cost might have been preserved by preventing the installing of new physical facilities that is on the other hand required. Raising to a higher standard in particular improved machinery by adding or replacing components of prospective wind turbine plants will mostly involve upgrading grid side converter and related control firmware. Additionally, with the present-day infrastructure of operational wind power plants, the overall reactive power leeway within easy reach for most of the active power operating points outperform the reactive power actually needed by grid code requirements. Under such set of conditions, additional dynamic reactive power backup can be supplied by wind turbines. Thus, the necessity to take into consideration a well-organized way of utilizing existing facilities like up-grading of existing wind farms to type-3, type-4 and type-5 wind turbine founded wind farms due to their ability to produce reactive power in modern renewable integrated electricity grid is highly advised. The Type-4 wind power turbine is more attractive due to its design flexibility and functions [33], and [34].

3. THE INSULATED GATE BIPOLAR TRANSISTORS (IGBTS)

The Insulated Gate Bipolar Transistor (IGBT) is the most generally utilized power semiconductor switch covering an extensive area of applications such as domestic, industrial motor control, traction, renewable power sources, and so on. Insulated gate bipolar transistors (IGBT), Integrated Gate Commutated Thyristor (IGCT) and MOS-Controlled Thyristor (MCT) are the three new designs of power devices. IGBT is the most widespread utilized power electronic equipment at present, the simplified equivalent circuit and circuit symbol of an IGBT are shown in Fig. 1, and Fig. 2 respectively. An IGBT is fundamentally a hybrid MOS-gated turn on/off bipolar transistor that combines the characteristics of the Metal Oxide Semiconductor Field Effect Transistors (MOSFET), Bipolar Junction Transistor (BJT) and thyristor [40] – [43].

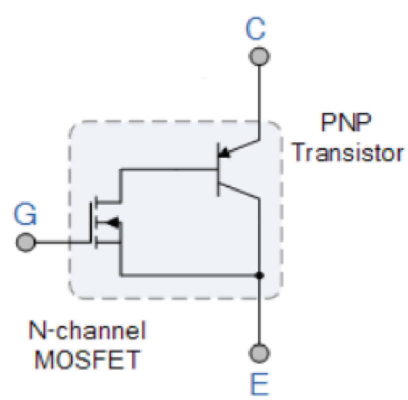

Figure 1 A simplified equivalent circuit of an IGBT [43]

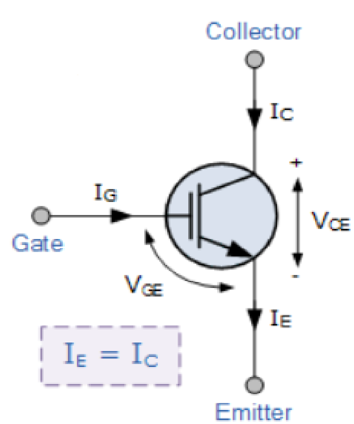

Figure 2 The circuit symbol of an IGBT [43]

The cross-section of an IGBT structure is shown in Fig. 3, this conception of IGBT has been opted for in order to stop hole current flow into the p-body region, and it is depicted by an n-diffusion below the p-body. This n-diffusion stops the hole flow, and electrons are supplied by the channel to support charge neutrality, raising in this manner the plasma distribution near the cathode [40], [44], [46].

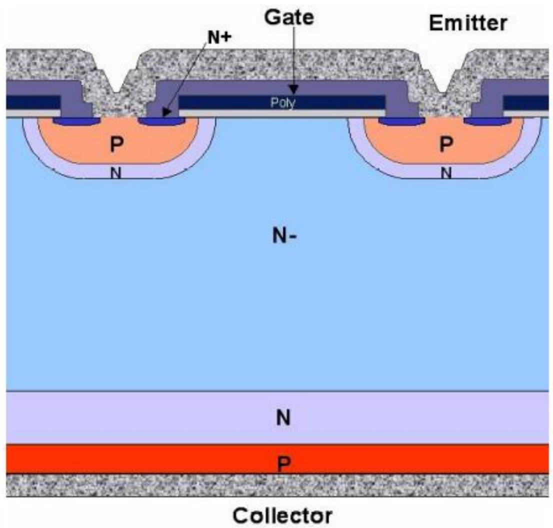

Figure 3 Cross-section of an enhanced-planar IGBT [44]

A fascinating Reverse-Conducting Insulated Gate Bipolar Transistor (RC-IGBT) cross section is shown in Fig. 4. As can be seen, the structure is including of a hole barrier layer, n-diffusion below the p-well, this is to make the best use of the IGBT performance and equally acting as a reduced p-emitter efficiency for the diode. Furthermore, a local lifetime control can equally be utilized below the p-body region. Very effective and robust IGBTs from 600V to 6.5kV are commercially obtainable, and inventions up to 8kV have been established [40], [45] – [46].

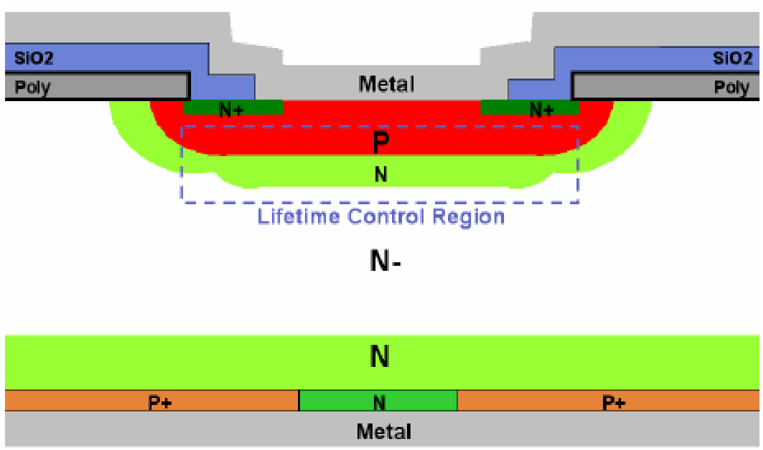

Figure 4 Cross-section of an RC-IGBT [45]

4. MATERIALS AND METHODS

Here, MATLAB/Simulink software have been utilized for the computer modelling of the system being investigated and implemented in excel worksheet. The Wind power source is attached at the beginning terminal of the electricity scheme arrangement, it is joined onto a 3Φ electricity scheme made up of 0.4 kV low voltage feeder with active power of 8 MW and a negative reactive power that is capacitive reactive power (Q_C) of 0.5 VAR. The 20-kV medium voltage feeder has an active power of 22 MW and a negative reactive power (Q_C) of 1.5 MVAR. The system has different values of positive reactive power for the three sets of data monitored, that is to say data 1, 2, and 3, then the 20-kV medium voltage electricity distribution grid is joined to a 20-kVelectric-power substation. Afterwards, a 20-kV medium voltage renewable wind power source utilizing IGBT power electronics converter is joined to the distribution electricity network for effectual reactive power production. Point One (1) and Point Two (2) are the beginning terminal and terminating end of the 20 kV MV electricity distribution system. The proposed system is realized using MATLAB/Simulink computer model, the scheme model has the 0.4 kV load joined at the terminating end of the electric-power line by a MV/LV transformer, and the 20-kV load is connected to the substation bus bar just at the beginning terminal of the distribution power line.

This is shown in Fig. 5. The parameters of the network is utilized to test the authenticity of the electricity network for the various load values, the 0.4 kV load has different Positive MVARs or Inductive Reactive Power (Q_L) values of 2, 2.25 and 2.5 MVARs respectively for data 1, 2, and 3 monitored, Active Power P (MW) is 8 MW, while the Capacitive Reactive Power Q_C (Negative MVAR) is 0.5 MVAR. And the 20 kV load has different Positive MVARs or Inductive Reactive Power (Q_L) values of 6, 6.5 and 7 MVARs respectively for data 1, 2, and 3monitored,the Active Power P (MW) for the 20 kV load is 22 MW, and the Capacitive Reactive Power Q_C (Negative MVAR) is 1.5 MVAR. To obtain each load value observed, the positive reactive power (Q_L) for each set of data's is increased, meaning that data 1 is raised by 12 %, while data 2, is raised afterwards by 24 %, The power factor (Cos φ) values for the 0.4 kV and 20 kV loads feeder power networks is calculated utilizing the equation stated below to establish evidence of the authenticity of the power system. For data 1, 2, and 3 monitored, the power factor (Cos φ) for Load 0.4 kV are 0.9829, 0.9769, and 0.9701 respectively. Also, considering data 1, 2, and 3 observed, the power factor for Load 20 kV are 0.9797, 0.9750, and 0.9701 respectively

$$\cos\varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}}$$

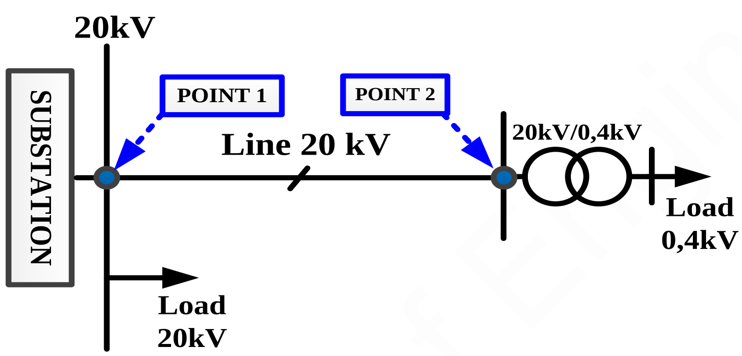

Figure 5 A scheme of the 20 kV MV distribution electricity system without the wind power source installed.

The 20 kV electricity distribution system with the wind power source placed at the beginning terminal of the power line is shown in Fig. 6. The wind farm has a synchronous generator and IGBT power electronics converter switches, which allows the production of reactive and active power by the distribution electricity scheme.

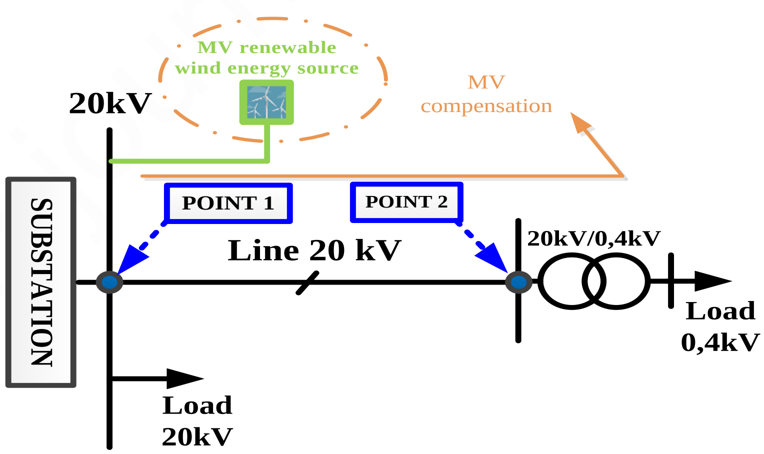

Figure 6 A scheme of the 20 kV MV electric-power Line with the wind power source placed just at the beginning terminal of the distribution electricity system

Power factor values measured when the Wind Farm is Switch OFF at the beginning terminal (Point One) for data 1, 2, and 3 are 0.9706, 0.9648 and 0.9587 for the 20 kV load, while at the terminating end (Point Two) of the 20 kV electricity distribution system for each set of data from 1 through 3, the power factor values obtained are 0.9768, 0.9700 and 0.9624respectively. But when the Wind Farm is Switch ON, the values obtained from point one is 0.9952, 0.9854 and 0.9773 for data 1, 2, and 3 measured, while at point two 0.9855, 0.9730, and 0.9675 power factor values where gotten for data 1, 2, and 3 recorded. The same results will be the case for the

0.4 kV load when the wind farm is switched OFF and ON. The differences in voltage (U_s-U_r) [kV]values at the beginning terminal and terminating end of the 20 kV electricity distribution line with the Wind Farm Switched OFF are 2.12, 2.2 and 2.27 respectively, and 2.27, 2.3 and 2.36 when the Wind Farm Switch ON. Power losses [kW] for data 1, 2, and 3when the Wind Farm is Switch OFF is 205.7, 269.8 and 310.2 respectively, and when the Wind Farm is Switch ON279.9 kW, 332.4 kW, and 386.5 kW were obtained respectively for data 1, 2, and 3 observed.

5. RESULTS AND DISCUSSION

Results from the analysis of the 20 kV electricity distribution system is presented in this part of the article, Fig. 7 shows the measured power factor values when the wind farm is joined at the beginning terminal of the electricity distribution line. The wind farm is switched OFF and ON, then readings are recorded at Point 1 and Point 2. It is observed that at Point 1 and Point 2for each set of data monitored from data 1 through 3, there is a decrease in the measured power factor values when the wind farm is switched ON, while the power factor values recorded also decreases when the wind farm is switched OFF. This is pictorially represented in Fig. 7. It is demonstrated that for the various data's monitored, reactive power is being made use of or utilized when the wind farm is switched OFF, but when the wind farm is switched ON reactive power is being produced and injected/administered onto the medium voltage electricity distribution line.

Analysis of Fig. 8, and Fig. 9, reveals the difference in voltage and power losses values measured from Point 1 and 2 respectively, it is shown that when the wind farm is switched OFF the network made use of or utilizes reactive power and the direction of power flow is from the voltage sending (U_s) terminal to the voltage receiving (U_r) terminal of the 20-kV MV electricity.

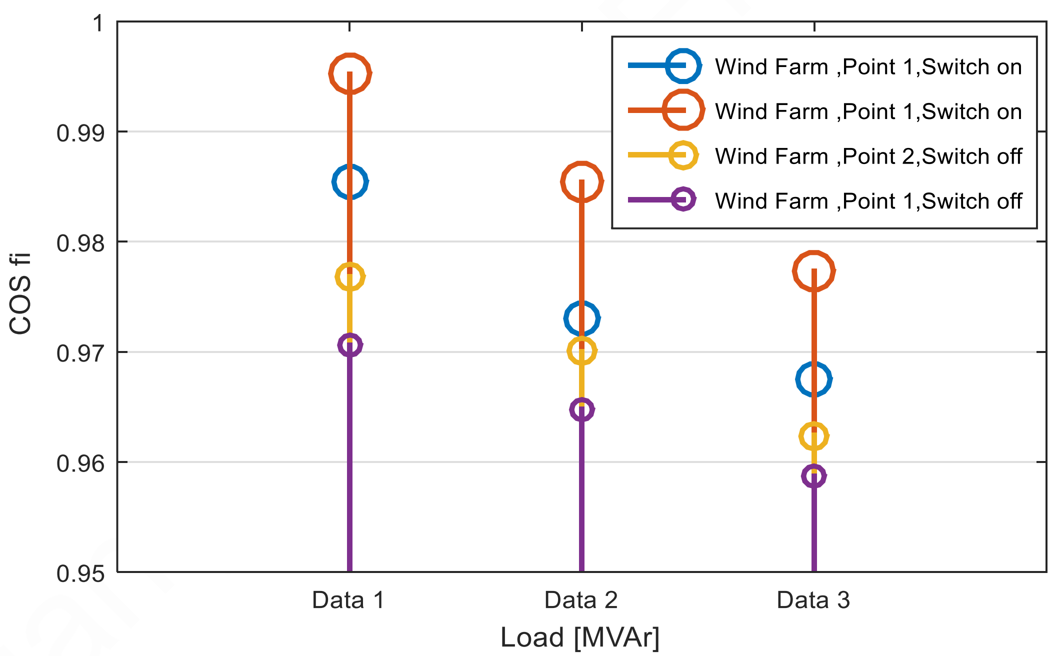

Figure 7 Power factor values measured at Point 1 and 2 on the 20-kV electricity distribution line, when the wind farm is switched OFF and ON.

Distribution network

While the results obtained when the wind farm is switched ON demonstrates that reactive power is being produced and injected/administered onto the electricity distribution system and the direction of power flow is from the voltage sending (U_s) terminal to the voltage receiving (U_r) terminal of the 20 kV MV electricity distribution network. Fig. 8, vividly shows that the voltage difference values monitored is large when the wind farm is switched ON as compared to the situation when the wind farm is switched OFF for the three data's observed from 1 through 3. While Fig. 9, shows that the electricity distribution system power losses progressively increase as data 1 is observed through to data 3, when the wind farm is switched OFF and ON.

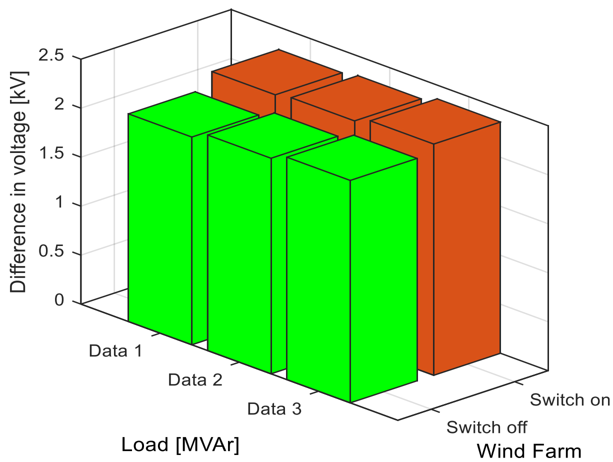

Figure 8 The difference in voltage values measured at Point 1 and 2 on the 20-kV electricity distribution line, when the wind farm is switched OFF and ON

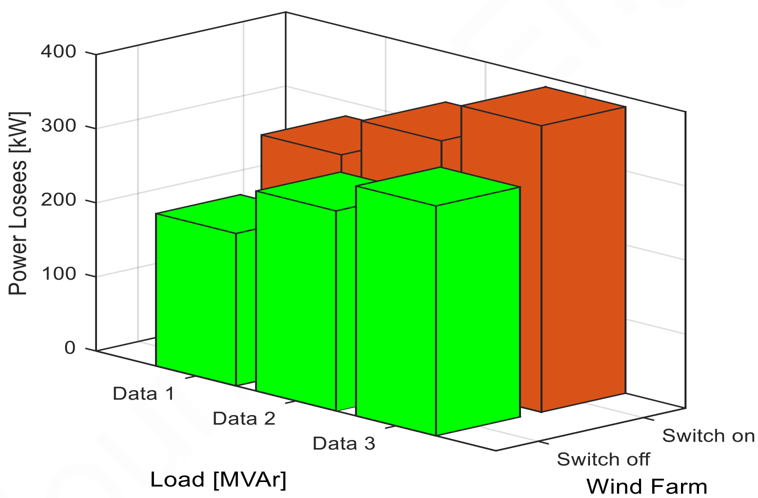

Figure 9 Power losses values measured at Point 1 and 2 on the 20-kV electricity distribution line, when the wind farm is switched OFF and ON

6. CONCLUSION

Reactive power production utilizing wind turbines is an area of research that wind turbine manufacturers have to take into consideration for the future growth of the industry. This research has established the fact that penetration especially of Type-1 and Type-2 wind power turbine technology that uses-up reactive power from the electricity grid in contrast with producing reactive power and with the present-day infrastructure of operational wind power plants in today's electricity grids, the sum total reactive power leeway obtainable for almost all the active power operating points exceed the reactive power needed by grid code requirements. Meaning that, supportive services which are nowadays provided largely by traditional generation means such as reactive power production should as well be acceptably supplied by wind power sources in a well-engineered manner. Productive utilization of wind power turbines for producing reactive power in wind farms can lower the monetary amount of operation and prolong the life of exclusive dynamic reactive power equipment's. Implying that in large-scale wind combined electricity network, it is needful to take into account the well-organized utilization of existing machinery like up-grading of wind farms in existence at this present time to Type-3, Type-4 and Type-5 wind turbine based wind farms owing to their capability to produce reactive power.

The Type-4 wind power turbine presents a substantial benefit of flexibility in design and operation as the output from the rotating machine is conveyed to the electricity grid via a full-scale back-to-back frequency converter. Reactive power producing capability of a wind turbine generating system has been buttressed with an exemplification utilizing MATLAB/Simulink model. Examination of the results gotten displays that when the wind power source is switched ON, the suggested electricity distribution system model was able to achieve maximal production of reactive power. The authors of this research work recommend the Type-4 wind turbine system as it guarantees substantial merit of flexibility in design and operation when utilized in an electrical power grid, this is a creative way of supplying reactive power support as per the increasing strict requirements of grid codes. Extra research assignments will be to maximally and exactly find a technique to unfold the issues of reactive power production, voltage control, and power losses in a more extensive electricity distribution system.

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Conflicts of Interest: The authors declare no conflict of interest.

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