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A novel scheme for control by active and reactive power utilized in gearless variable speed wind turbine system with PMSG connected to the grid

Introduction. *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.* ***Purpose****. The main goal of this work is developing a control scheme for a variable speed wind turbine generator in order to produce utmost power from varying wind types, and variable wind speed.* ***Novelty.*** *This research paper presents an IGBT power converter control scheme for active power in relation to wind speed and reactive power by adjusting Q-reference (Q_{ref}) value in a gearless variable speed wind turbine with permanent magnet synchronous generator.* ***Methods****. An effective modelling and control of the wind turbine with the suggested power converter is executed by utilizing MATLAB/Simulink software. The control scheme consists of both the wind turbine control and the power converter control. Simulation results are utilized in the analysis and deliberation of the ability of the control scheme, which reveals that the wind turbine generator has the capability to actively sustain an electric power grid network, owing to its ability to independently control active and reactive power according to applied reference values at variable wind speed.* ***Practical value****. This research can be utilized for assessing the control methodology, the dynamic capabilities and influence of a gearless variable-speed wind energy conversion system on electric power grids. A case study has been presented with a (3·10 MW = 30 MW) wind farm scheme.* References 67, tables 2, figures 19.
Key words: **wind turbine, wind farm, gearless wind turbine, variable-speed wind turbine, IGBT power converter, multi-pole permanent magnet synchronous generator, full-scale power converter.**

Вступ*. Внаслідок зростання цін на викопне паливо та використання найсучасніших технологій, дедалі більше побутових та комерційних споживачів електроенергії встановлюють вітряні турбіни. Мотивація полягає в тому, щоб скоротити рахунки за електроенергію та викиди вуглекислого газу.* ***Мета****. Основною метою цієї роботи є розробка схеми управління вітряним генератором зі змінною швидкістю для отримання максимальної потужності від різних типів вітру та змінної швидкості вітру.* ***Новизна****. У даній дослідницькій роботі представлена схема управління силовим IGBT перетворювачем для активної потужності в залежності від швидкості вітру та реактивної потужності шляхом регулювання значення Q-еталона (Q_{ref}) у безредукторній вітровій турбіні з регульованою швидкістю та синхронним генератором із постійними магнітами.* ***Методи****. Ефективне моделювання та керування вітровою турбіною з запропонованим перетворювачем потужності здійснюється з використанням програмного забезпечення MATLAB/Simulink. Схема управління складається з управління вітряною турбіною і з управління силовим перетворювачем. Результати моделювання використовуються для аналізу та обговорення можливостей схеми управління, що показує, що генератор вітрової турбіни здатний активно підтримувати електроенергетичну мережу завдяки своїй здатності незалежно контролювати активну та реактивну потужність відповідно до застосовуваних еталонних значень при змінній швидкості вітру.* ***Практична цінність****. Це дослідження може бути використане для оцінки методології управління, динамічних можливостей та впливу безредукторної системи перетворення енергії вітру зі змінною швидкістю на електричні мережі. Наведено тематичне дослідження зі схемою вітряної електростанції (3·10 МВт = 30 МВт).* Бібл. 67, табл. 2, рис. 19.
Ключові слова: **вітряна турбіна, вітряна електростанція, безредукторна вітряна турбіна, вітряна турбіна з регульованою швидкістю, силовий IGBT перетворювач, багатополюсний синхронний генератор з постійними магнітами, повномасштабний силовий перетворювач.**

Introduction. Presently, there has been progressive advancement in modern renewable wind power plant technology. Specifically, the gearless wind power plant with permanent magnet synchronous generator is utilizing full-scale power converter. Electric power 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 [1-11].

The permanent magnet synchronous generators (PMSGs) are widely utilized in wind turbines owing to their excellent operation and power quality characteristics in the variable speed wind energy transformation systems, its turbine control systems are more complex when weighed with constant speed wind power converter systems. The fixed speed wind turbine implementations are not normally chosen due to their low capabilities and their power quality is not at a required level [12-18]. PMSGs are among the finest solutions for wind power plants. Low-speed multi-pole permanent magnet synchronous generators are free from maintenance and can be utilized in diverse climatic environment. A traditional megawatt-scale wind turbine generator composes of a low-speed wind turbine rotor, gearbox, and high-speed electric generator. The utilization of gearbox gives rise to several technological issues in a wind turbine generator, as it requires frequent maintenance, it multiplies the weight and total cost of the wind turbine generator, it produces noise, and also multiplies power losses. These issues can be solved by utilizing a substitute, a direct-drive low-speed permanent magnet synchronous generator [18-20]. But a more appropriate solution and way out is to utilize a gearless wind turbine generator.

A multi-pole synchronous generator attached to a power converter can function at low speeds, so that a gear can be excluded. A gearless structure symbolizes a proficient and durable explanation, which can be immensely advantageous mainly for offshore utilizations. Besides, owing to the permanent magnet excitation of the generator the direct current excitation structure can be removed thereby further reducing once more the weight, losses, costs and maintenance demands [20, 21]. The ability of a PMSG wind turbine is consequently evaluated to be higher than alternative ideas [22, 23]. Nevertheless, the drawbacks of the permanent magnet excitation are the excessive costs of permanent magnet constituents and a fixed excitation, which can't be adjusted in accordance with the functional consideration [2].

The dependability of the variable speed wind turbine can be ameliorated notably by utilizing a direct drive PMSG. The PMSG has been given considerable attention in wind power implementation reason being its property of self-excitation, which permits functioning at a high-power factor and high capability [24]. The utilization of permanent magnet in the rotor of the PMSG causes it non-essentially to provide magnetizing current using the stator for constant air-gap flux; the stator current requires just to be torque generating.

Therefore, for the same output, the PMSG will function at a higher power factor due to the absence of magnetizing current. To produce utmost power from varying wind, variable speed functioning of the wind turbine generator is obligatory. This needs a highly-developed control scheme for the generator [25]. A control scheme for the generator side converter with utmost output of a PMSG wind turbine needs to be put in place. The generator side switch mode rectifier is controlled to obtain utmost energy from the wind. This necessitate only one active switching device (IGBT), which is utilized to control the generator torque in order to obtain utmost energy from the wind turbine generator. A full scale IGBT back-to-back voltage source converter, as indicated in Fig. 1 by which the generator is linked to the electric power grid, permits full controllability of the system. As a result of strengthened electric power grid codes, wind turbine generators with full scale power converter will be more utilized in the near future. Since power converter of such wind energy system decouples the generator system from the electric power grid, fault-ride through and grid support can be easily attained [2].

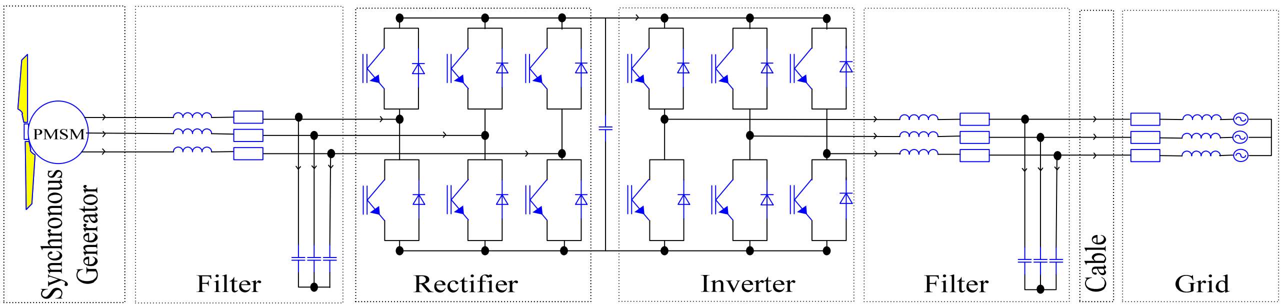


Fig 1. Modeling scheme and control concept of the variable-speed wind plant with multi-pole permanent magnet synchronous generator

The goal of the paper is the development of control scheme for a variable speed wind turbine generator.

An effective model of the whole wind power generator system is performed using Matlab/Simulink software environment. The scheme includes models of the aerodynamic and mechanical sections of the wind turbine generator as well as its electric power and control systems. The PMSG wind turbine generator control methodology is accomplished by harmonized regulation of the power converters and the wind turbine generator control systems. The generator-side and the grid-side has identical power converter control systems, there is also the gearless drive converter and aerodynamics pitch angle control mechanism. The wind turbine generator rating of this research article is 10 MW. A case study of a 3·10 MW = 30 MW wind farm is thereafter presented.

Arrangement of the proposed wind turbine system and mathematical model of the PMSG. The normal schematic arrangement of a variable-speed wind turbine established on a PMSG and full-scale power converter is shown in Fig. 1. It is made up of two main parts. First is the wind turbine generators mechanical part, that is the gearless drive converter and the aerodynamics pitch angle control. Second is the wind turbine generators electrical part that is the multi-pole PMSG full-scale frequency converter and its control mechanism [26]. As can be seen in Fig. 1 the aerodynamic rotor of the wind power arrangement is precisely matched with a gearless generator. The synchronous generator is linked to the electric power grid by means of a full-scale frequency converter scheme, which is utilized to control the speed of the generator and power flow to the grid side of the wind turbine generator arrangement. The permanent magnets are installed on the generator rotor, making provision for fixed excitation of the generator. The power gotten from the generator is fed via the stator windings into the full-scale frequency converter, which changes the varied generator frequency to constant grid frequency. The full-scale frequency converter structure is made up of a back-to-back voltage source converter, that is the generator-side converter and the grid-side converter joined by means of a DC-link, which is then controlled by IGBT switches. Figure 1 is the proposed variable-speed wind turbine generator under consideration, a PMSG is installed to the electricity grid with the aid of a back-to-back arrangement of converters. The first converter, which is the generator-side converter, is joined to the stator windings of the PMSG. While the second converter, which is the grid side converter is linked to the electricity grid at the point of common coupling with the aid of AC filter. The DC terminals of the two converters are joined together by means of DC shunt capacitor. The power strategy of the converters contains a three-leg voltage source inverter. Nevertheless, diverse control strategies hinged on the systems control function can be applied to the inverter switches [26-33]. Wind turbines can either be Fixed Speed Wind Turbines with Induction Generator (FSWT-IG) or Variable Speed Wind Turbines with Permanent Magnet Synchronous Generator (VSWT-PMSG). The former has the benefits of mechanical manageability, small specific mass, resilient structure, and economical. Nevertheless, its limitations include restricted capacity for power quality control and terminal voltage variation during steady state circumstance, owing to the unmanageable reactive power utilization. The latter is a favourable and appealing variety of wind turbine idea, in which the PMSG can be straightly operated by a wind turbine and attached to the electric power grid network by means of AC/DC/AC power converter. The benefits of the VSWT-PMSG are as follows:

- it neither has gearbox nor brushes, consequently it has higher reliability;
- it has no extra power provision for excitation.

The power converter allows extremely pliable control of active and reactive power in instances of typical and disrupted grid circumstances [2, 17, 21, 34, 35]. PMSGs occupy a significant part in direct drive wind energy production systems for changing mechanical power into electrical power. The dynamic configuration of the PMSG is obtained from the two-phase synchronous reference frame, in which the q-axis is 90° leading of the d-axis in conformance with the orientation of rotation. The harmonization connecting the (d-q) revolving reference structure and the abc-three phase structure is sustained by utilizing a phase locked loop. A detailed mathematical modelling of the PMSG is a necessary condition for the design of the machine control algorithms and the examination of the steady-state and dynamic features of the wind power transformation scheme. Direct drive wind turbine generators, distinguished as highly effective or efficient and requires low maintenance procedures, provides favorable possibilities for future implementations [7, 36-38], particularly offshore applications. In order to do away with the gearbox the generator is constructed for low speed performance maximally between 15-20 rpm. This characteristic has made synchronous generators the only choice for low speed wind turbine utilizations. Synchronous generators magnetic field is provided with rotor excitation, but in the instance of the PMSG the direct current excitation scheme can be removed, which necessitate minimizing losses and exclusion of slip rings and consequently the maintenance requirements of the system [2, 39, 40]. To realize independent control strategy of the active and reactive power, the d-axis and q-axis equivalent circuits is utilized in the drive converter arrangements [41].

The phasor diagram of the PMSG model is shown in Fig. 2. While the mathematical model of the PMSG in both natural (abc) three-phase stationary reference frame and (d, q) synchronously rotating reference frame is developed as follows writing the stator voltage equation (in time domain):

$$u_S = R_S \cdot i_S + L_S \cdot \frac{\mathrm{d}i_S}{\mathrm{d}t} + e . \quad (1)$$

If (α, β) is the stator coordinate system, we can write (1) in these coordinates:

$$u_S(\alpha,\beta) = R_S \cdot i_S(\alpha,\beta) + L_S \cdot \frac{\mathrm{d}i_S(\alpha,\beta)}{\mathrm{d}t} + e . \quad (2)$$

Then the voltage and current equations in the rotor coordinate system become:

$$\hat{U}_S(d,q) = U_d + jU_q ; \quad (3)$$

$$\hat{I}_S(d,q) = I_d + jI_q , \quad (4)$$

where R_S is the stator resistance; L_S is the stator inductance; U_S is the stator voltage; e is the excited voltage; i_d is the instantaneous real power current; i_q is the instantaneous reactive power current, i_S is the whole current and γ is angular velocity.

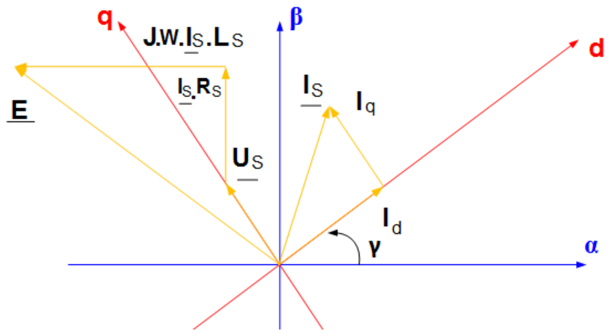


Fig. 2. The phasor diagram of the PMSG model

The equations of the synchronous generator are:

$$\frac{\mathrm{d}\Psi_d}{\mathrm{d}t} = U_d - R_1 \cdot I_d - \Omega_L \cdot \Psi_q ; \quad (5)$$

$$\frac{\mathrm{d}\Psi_q}{\mathrm{d}t} = U_q - R_1 \cdot I_q - \Omega_L \cdot \Psi_d , \quad (6)$$

where Ψ_d and Ψ_q are the components of the magnetic field; Ω_L is the electrical angular velocity.

So the equations of the magnetic field are:

$$\Psi_d = \Psi_{pm} - L_d \cdot I_d ; \quad (7)$$

$$\Psi_q = L_q \cdot I_q , \quad (8)$$

where Ψ_{pm} is the synaptic magnetic field with the rotor.

So the equation of the torque is:

$$M_{MI} = \frac{3}{2} \cdot P_P \cdot \left(\Psi_d \cdot I_q - \Psi_q \cdot I_d\right), \quad (9)$$

where M_{MI} is the torque of the machine.

We have the mechanical velocity:

$$J \cdot \frac{\mathrm{d}\Omega_m}{\mathrm{d}t} = \left(M_{MI} - M_W\right). \quad (10)$$

So we can calculate the velocity without using measurements by using the following equation:

$$\Omega_m = \frac{1}{J} \cdot \int \left(M_{MI} - M_W\right)\mathrm{d}t, \quad (11)$$

where M_W is the load torque; J is the whole torque inertia.

These principles is used in the mathematical modeling of the PMSG rotor as shown in Fig. 3, which illustrates the schematic diagram of the PMSG rotor utilized in this research work.

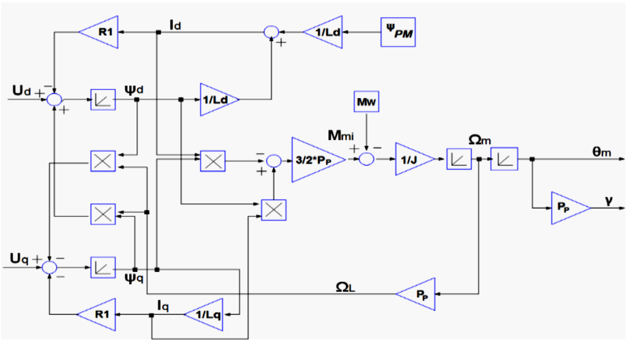


Fig. 3. Schematic diagram of the PMSG rotor

The proposed IGBT power converter control configuration. The power converter control arrangement is split into two controllers: a control scheme for the generator side converter and another control scheme for the grid side converter. The grid side converter should be an active inverter, since it changes DC link voltage to AC grid voltage with fixed frequency of an electric power system, the generator side converter can non-mandatory be made up of passive elements, e.g. a diode rectifier, or active elements such as IGBTs or GTOs. In whatever way, the most advantageous utilization and controllability of a PMSG can be realized if an active inverter is also utilized on the generator side, take for instance the IGBT voltage source converter as suggested in Fig. 1. Nevertheless, IGBT converters are costly and must be guarded or protected from over-currents and over-voltages. IGBTs are composite of bipolar-metal-oxide semiconductor, which possesses the merits of low on-state resistance, voltage regulation of the gate and broad unharmed working locality. IGBTs are as well one of the utmost essential constituents as well as broadly utilized power piece of equipment in power electronics in spans above 1 kV and 1 kW, the most utilized power equipment for commercial implementations are IGBTs. Various control schemes can be implemented with the power converter, including of: unity power factor control; maximum torque control; and the constant stator voltage control of the generator. The standard three phase bridge converter with three legs has been utilized in this research work, each has two switches, that is IGBT with antiparallel diode, operating under pulse width modulation (PWM) with a frequency of about 10 kHz. The rectifier and inverter consist of the same elements and works with the same principle, they are traditionally known as Voltage Sourced Converters (VSC) [2, 28-29, 42-47].

The PMSG frequency rectifier and electric power grid frequency inverter. The organization of the control plan of the frequency inverter for the grid side is displayed below in Fig. 1 the same frequency converter is utilized for the control plan of the generator side. The grid side converter is an active inverter, while the generator side converter is made up of passive diode rectifier, the rectifier and inverter consist of the same elements and works with the same principle. The control signal employed with the IGBTs gate switching is three phase sinusoidal voltage which originated from the d-q axis signal. The grid side inverter controls the DC link capacitor voltage at the set value, so that the active power can be interchanged effectively from the PMSG to the electric power grid. It also controls the reactive power output to the electric power grid in order to control the grid side voltage. In this control scheme, the d-axis of reference frame is oriented along the grid voltage. [36, 48].

Mathematical model of the gearless drive power converter. The drive converter arrangement of a gearless wind turbine generator comprises mainly of the turbine and generator. The major sources of inertia of this system lie in the turbine and generator. The Eigen-frequency of the drive-converter is quite low and within the bandwidth that is usually taken into consideration in power system dynamics simulations, it ranges from 0.1–10 Hz. A wind turbine generator transforms wind power into electrical power. Its functioning attribute is extraordinarily non-identical to that of traditional electrical power sources. The output power of a wind turbine generator can be different over a broad extent between zero and the adjudged ability value, in an unsystematic but continual manner. In multi-pole generators, the same electrical angle indicates a much smaller mechanical angle than in generators with small number of poles. The pitch angle controls the generator speed, meaning that the input in the controller is the error signal connecting the reference generator speed and the measured generator speed. The pitch angle controller places a limit on the rotor speed when the nominal generator power has been attained, by restricting the mechanical power produced from the wind and consequently reinstating the balance connecting electrical and mechanical power [8, 49-52].

The aim of the driving converter utilized in the proposed wind turbine generator scheme is to determine the moment and the time of contact for each switch. The technique of driving is PWM, which utilizes digital signals to control power applications, as well as being sufficiently uncomplicated to change back to analogue with the least possible hardware. Figure 4 gives an idea on how to drive this converter [28, 29]. From Fig. 4 the equations given below in (12)–(14) are generated:

$$I_{ctr1} = \underline{V_1}(t) = 0.5 \cdot AF \cdot \sin(\omega t); \quad (12)$$

$$I_{ctr2} = \underline{V_2}(t) = 0.5 \cdot AF \cdot \sin\left(\omega t + \frac{2\pi}{3}\right); \quad (13)$$

$$I_{ctr3} = \underline{V_3}(t) = 0.5 \cdot AF \cdot \sin\left(\omega t - \frac{2\pi}{3}\right), \quad (14)$$

where I_{ctr1}, I_{ctr2}, and I_{ctr3} are the outputs of the control circuit, and AF is the amplitude function.

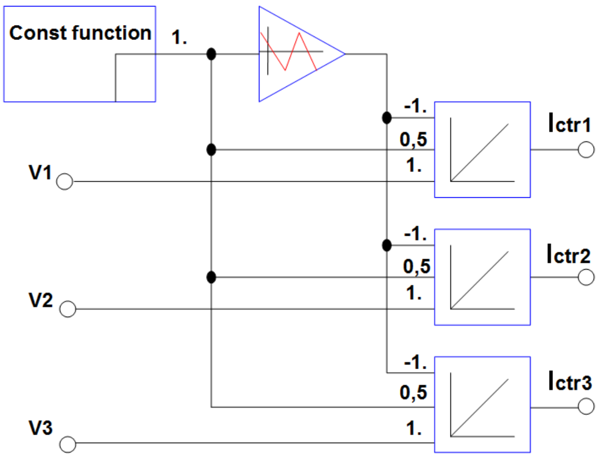


Fig. 4. Generated control currents function structure

PMSG and electric power grid converter control circuits. The constant stator voltage control mechanism is appraised to be of utmost advantage in gearless wind turbine applications, this control structure is applied in the simulation model of the proposed scheme. The DC-link voltage is kept constant to ensure that the generated active power is fed via the DC-link to the electricity grid, all this is done to make sure that no energy is dissipated in the DC-link [2]. Figure 5 illustrates the control circuit of the synchronous generator. It controls the currents of the synchronous generator in the rotor coordinate order and the input quantities which are stator currents (I_{L1}, I_{L2}, I_{L3}) changed into the stator coordinate system (α, β). These currents (I_α, I_β) are rotated from the stator coordinate system to the rotor coordinate system (d, q) by utilizing the vector negative adapter (VD-) technique [28, 46], the electric angle is gotten from the model of the synchronous generator. This then makes the stator currents in the rotor to be in the coordinate system (I_d, I_q) and both the constant and fixed currents are stabilized, which brings about a good assumption for the control mechanism. I_d is utilized to control the reactive power and I_q is utilized to control the synchronous generator torque [45]. Also (I_d, I_q) are compared with reference values ($I_{d.ref}$, $I_{q.ref}$) and the product of the deviation is sent to the PI controller. The output is a continues disengagement process to get driving vectors in the rotor coordinate system ($V_{d.ctr}$, $V_{d.ctr}$). These are then transformed to the stator coordinate system ($V_{\alpha.ctr}$, $V_{\beta.ctr}$) [46] and afterwards it is changed to vectors (V_{ctr1}, V_{ctr2}, V_{ctr3}) in the three-phase system. This process as explained above provides switch-off and switch-on for rectifier IGBT switches.

If the DC-link voltage remains constant by utilizing the generator-side converter control, the active power of the generator is conveyed through the DC-link to the grid-side converter. Consequently, the active power produced by the wind turbine can be controlled using the grid side converter. Owing to the converter mechanism used, the reactive power operational point of the generator side and the grid side converter are fully decoupled. This means that the reactive power, which is finally supplied to the electricity grid network, can be independently controlled by the grid side converter. Hence, the same control mechanism is utilized on both the generator and the grid network. The control circuit of the grid network is vividly shown in Fig. 6 [2, 28, 46].

Simulation results of the wind turbine design. To ensure a thorough evaluation of the functioning of the control mechanism for the variable speed wind turbine idea with PMSG, performed in the Matlab/Simulink software environment, a set of simulations with wind speed having the characteristics of no turbulence, no tower shadow etc. is performed. The wind turbine rating used is 10 MW. The nominal power of the wind turbine generator is 10/0.9 = 11.11 MVA. And the reactive power is regulated through the input parameter of Q_{ref} (that is the phase angle between the stator voltage and current of the PMSG) and it is generated in proportion to the nominal power. Three wind speed values have been observed, these are wind speed at points 5 m/s, 10 m/s, and 15 m/s, and Q_{ref} values from 0–1 p.u., from Fig. 7 and Fig. 8, it is observed that as the value of Q_{ref} increases from 0–1 p.u. there is a corresponding increase in the reactive power values i.e. from 0–11.11 MVAr. The active power at wind speed points 5 m/s, 10 m/s, and 15 m/s also increases too in value i.e. 5 m/s = 0.64 MW, 10 m/s = 5.56 MW, 15 m/s = 10 MW respectively. The obtained results for the wind speed and Q_{ref} is shown in Fig. 7, which depicts the graphical illustration of measured reactive and active power values and Fig. 8, showing comparison between measured values of active and reactive power. Hence, the results in Fig. 7,*a* shows that as Q_{ref} increases, there is a corresponding increase only in the reactive power values observed. And in the same vein Fig. 7,*b* shows that as wind speed is increased, there is a corresponding increase only in the active power values observed. Therefore, it can be inferred from simulation results that Q_{ref} has effect only on the observed reactive power values and the turbine wind speed has effect only on the values of active power. For simplicity, the 3D and 2D explanation of the results is further illustrated in Fig. 8,*a*,*b* respectively.

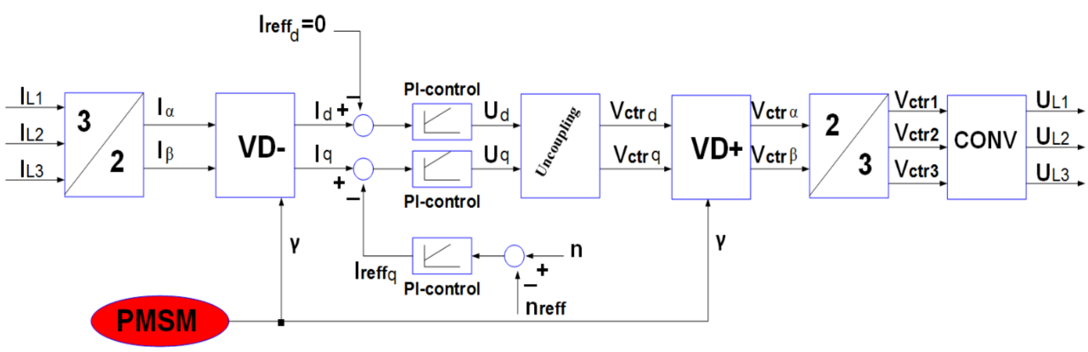


Fig. 5. The control circuit of the synchronous generator

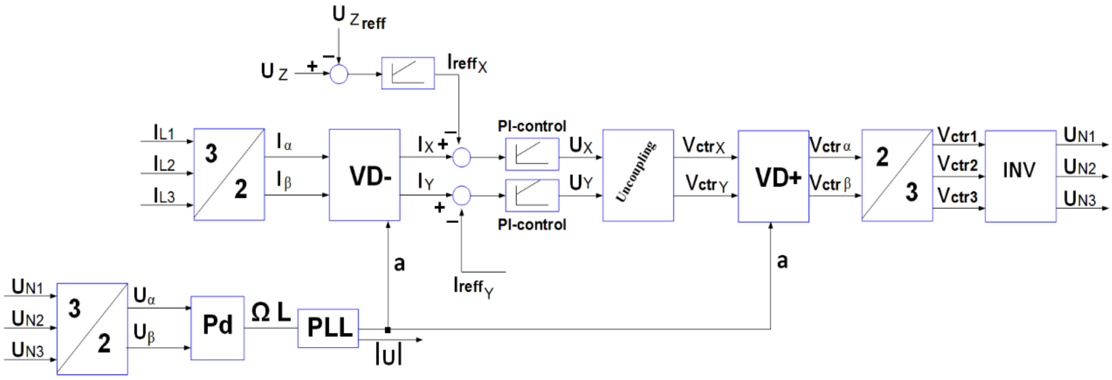
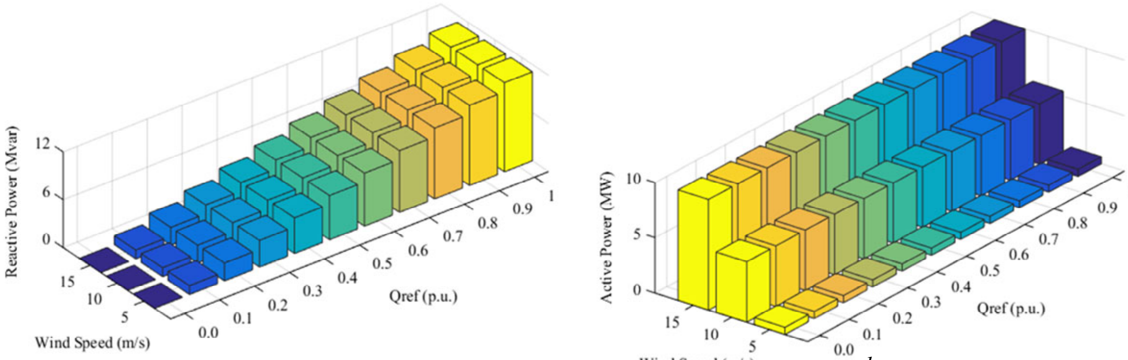
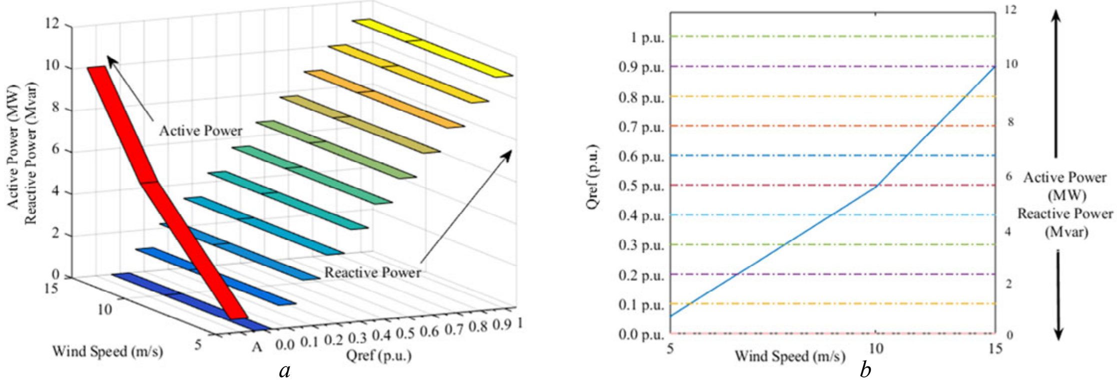


Fig. 6. The control circuit of the grid network



a *b*

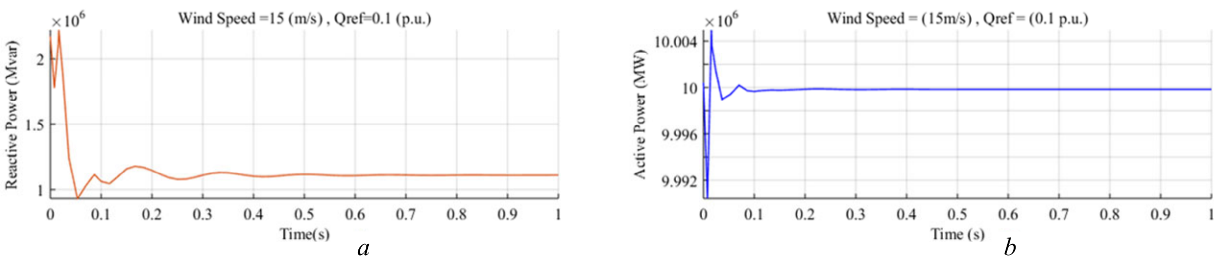
Fig. 7. Graphical illustration of measured values: *a* – reactive power; *b* – active power



a *b*

Fig. 8. Comparison between measured values of active and reactive power: *a* – 3D view; *b* – 2D view

Figures 9,*a*,*b* show the output values of reactive power and active power supplied to the network at operational point of 15 m/s and Q_{ref} value of 0.1 p.u. it is observed that the time to reach steady state is $T = 0.25$ s. Also Fig. 10,*a*,*b* show the output values of reactive power supplied to the network at the operational point of 10 m/s and 15 m/s respectively and the observed time to reach steady state for Q_{ref} values of 0.1 p.u. and 0.2 p.u., although there were sudden changes in current, the time to reach stable control of the system is very small $T = 0.25$ s. All these show the validity of the system and to further affirm that the proposed system is functional. The symmetrical and sinusoidal voltage wave form of the system is shown in Fig. 11, which further buttress the validity of the system.



a *b*

Fig. 9. The output values of reactive (*a*) and active (*b*) power supplied to the grid network at the operational point of 15 m/s

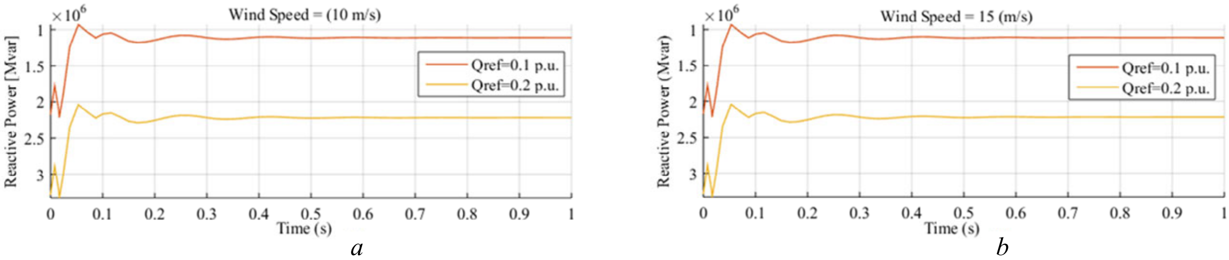


Fig. 10. The output values of reactive power supplied to the grid network at operational point of 10 m/s (*a*) and 15 m/s (*b*)

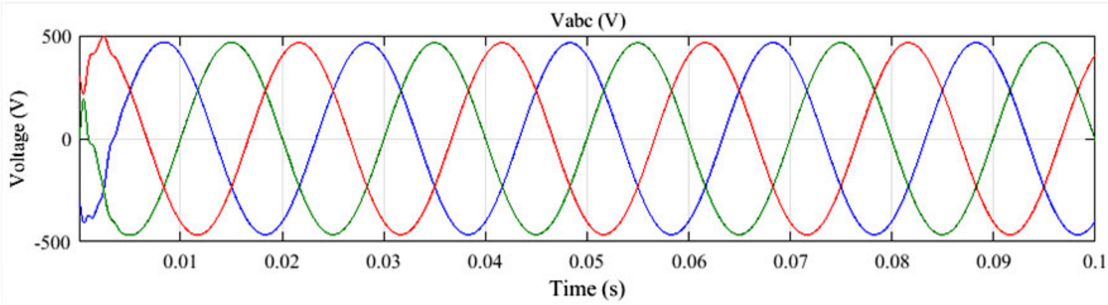


Fig. 11. Symmetrical and sinusoidal voltage wave form of the system

Novelty of simulation scheme. The novelty of this simulation scheme is the use of the Insulated Gate Bipolar Transistor (IGBT) switching device and the Type-4 wind turbine generator. 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. 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. The latest advancement in switching devices is playing a very significant part in the evolution of higher power electronics converters for wind power turbines with increased reliability and efficiency. The principal selections are mainly IGBT modules, IGBT press pack, and IGCT press pack. The press-pack technology brings about an increase in reliability, still to be scientifically demonstrated but known from industrial practice, higher power density, that is easier stacking for series connection, and better cooling ability at the price of a higher cost in contrast to power modules. Press-pack IGCT is known to support the advancement of MV power converters and are already state of the art technology in high-power electric drives such as utilized in oil and gas applications, but not yet universally adopted in the wind turbine industry owing to cost issues [53-64]. The Type-4 wind turbine as shown in Fig. 12 presents a great deal of flexibility in its design and operation as the output of the rotating machine is sent to the electricity grid via a full-scale back-to-back frequency converter.

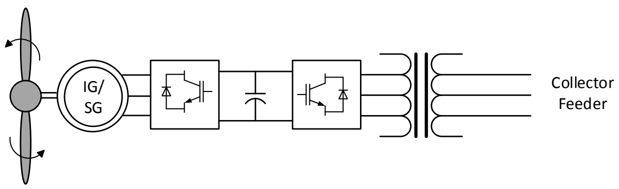


Fig. 12. A typical configuration of a Type-4 wind turbine generator

The wind turbine is permitted to rotate at its optimal aerodynamic speed, which results in a wild alternating current output from the machine. Furthermore, the gearbox might be completely remove or gotten rid of such that the machine spins at a slow wind turbine speed and produces an electrical frequency that is well below that of the electricity grid. This is no issue for a Type-4 wind turbine, as the inverters changes the power, and offer the potentiality of reactive power provision to the electricity grid, much like the Static Synchronous Compensator (STATCOM). The rotating machines of the Type-4 wind turbine built as wound rotor synchronous machines, is comparable to traditional generators found in hydroelectric power plants with control of the field current and high pole numbers, as permanent magnet synchronous machines or as squirrel cage induction machines. Nonetheless, the Type-4 turbine is able to control both real and reactive power flow, irrespective of what kind of machine is utilized [65-67].

Case study. Here, the wind farm rating used is (3·10 MW = 30 MW) 30 MW, three of the 10 MW wind turbine generators designed is utilized in this case study. The reactive power is regulated through the input parameter of Q_{ref} and it is generated in proportion to the nominal power. Three wind speed values are observed at, i.e. points 5 m/s, 10 m/s and 15 m/s respectively. Q_{ref} values is from 0 – 1 p.u., as the value of Q_{ref} increases from 0 – 1 p.u., there is a corresponding increase in the reactive power values i.e. from 0 – 33.33 MVAr. The active power at wind speed points 5 m/s, 10 m/s, and 15 m/s also increases too in value i.e. 5 m/s is 1.92 MW, 10 m/s is 16.68 MW, and 15 m/s is 30 MW. The MV wind farm comprises of a medium-voltage, passive rectification, AC/DC converters, and MV interconnection and distribution system, as illustrated in Fig. 13. While the single line diagram of the wind farm scheme showing its vector components is shown in Fig. 14.

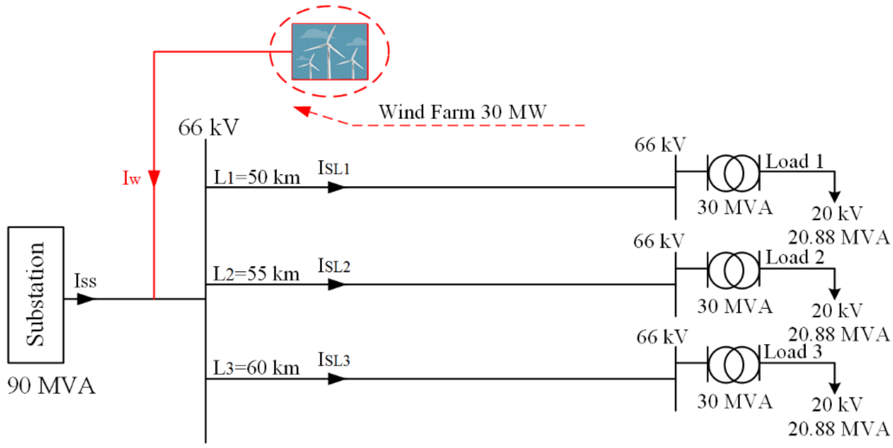


Fig. 13. Scheme of the wind farm connected distribution grid network

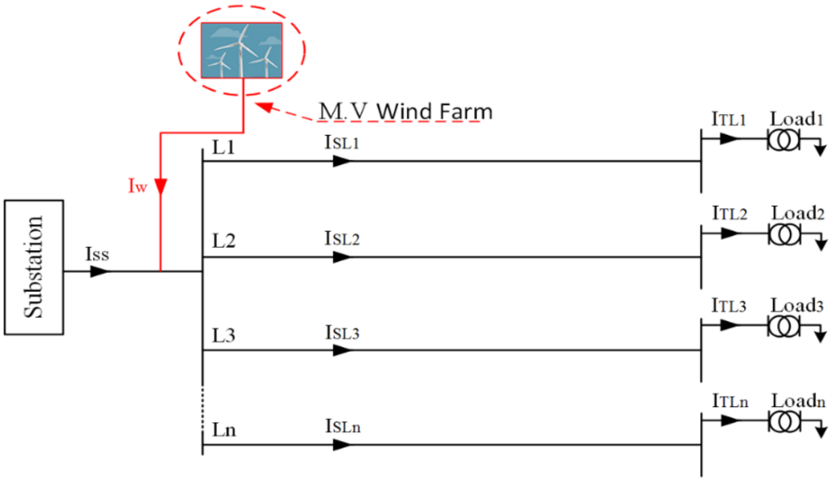


Fig. 14. Single line diagram of the wind farm scheme showing its vector components

The wind energy compensation strategy is connected to the electric power substation as shown in Fig. 14 considering its vector components:

$$I = I_{SS} + I_W, \tag{15}$$

where I_{SS} is the total substation line current; I_W is the wind farm line current.

The power losses on the line are given by:

$$\Delta P = 3 \cdot I_L^2 \cdot R_{1L} . \tag{16}$$

And the difference in voltage (voltage drop) of each phase is given by:

$$\Delta V = I_L \cdot Z_L. \tag{17}$$

From Fig. 14 and (16) the following power equation is deduced:

$$\Delta P_{LLn} = 3 \cdot \left(I_{SLn}^2 \cdot R_{1LLn} \right), \tag{18}$$

where I_{SLn} is the line current supplied to n^{th} number of power lines from the substation; R_{1LLn} is the resistance of n^{th} number of lines; ΔP_{LLn} is the active power losses of n^{th} number of lines; $n = 1,2,3,...,n$ (n is the number of lines).

Similarly, from Fig. 14 and (17):

$$\Delta V_{LLn} = I_{SLn} \cdot Z_{LLn}, \tag{19}$$

where ΔV_{ALLn} is the difference in voltage drop on n^{th} number of lines; Z_{LLn} is longitudinal impedance of n^{th} number of lines.

From (18), (19) the matrix equations for power losses and difference in voltage drop of the substation lines are given in (20), (21) respectively:

$$\left\{ \begin{array}{l} \Delta P_{LL1} = 3 \cdot \left(I_{SL1}^2 \cdot R_{1LL1} \right) \\ \Delta P_{LL2} = 3 \cdot \left(I_{SL2}^2 \cdot R_{1LL2} \right) \\ \Delta P_{LL3} = 3 \cdot \left(I_{SL3}^2 \cdot R_{1LL3} \right) \\ \quad \vdots \qquad\quad \vdots \qquad \vdots \\ \Delta P_{LLn} = 3 \cdot \left(I_{SLn}^2 \cdot R_{1LLn} \right) \end{array} \right\}, \tag{20}$$

$$\left\{ \begin{array}{l} \Delta V_{LL1} = I_{SS1} \cdot Z_{LL1} \\ \Delta V_{LL2} = I_{SS2} \cdot Z_{LL2} \\ \Delta V_{LL3} = I_{SS3} \cdot Z_{LL3} \\ \quad \vdots \qquad\quad \vdots \qquad \vdots \\ \Delta V_{LLn} = I_{SSn} \cdot Z_{LLn} \end{array} \right\}. \tag{21}$$

To measure the reactive power Q_G generated from the wind farm, and the active power P_G generated from the wind farm, the Q_{ref} is increased in percentage steps of 5, step 1 is when the wind farm is switched OFF, while for steps 2 to 5 the wind farm is switched ON as depicted in Table 2. Also the values of Q_{ref} is varied from step 2 to step 5 in order to produce reactive power from the wind farm according to the usage of reactive power by the load. The measured reactive power Q_G generated by the wind farm increases, while the measured active power P_G is constant for step 2 to 5 as tabulated in Table 1. The wind farm has supplied reactive power in order to influence the voltage profile of the distribution grid. While the flow of active power is very much essential for the distribution line to operate. Table 2 shows the measured values of reactive power Q_L, active power P_L and apparent power S_L for one load of step 1 to 5. For step 1, the wind farm is switched OFF, while the wind farm is switched ON for steps 2 to 5. It is seen that the reactive load of the wind farm for one load, increases progressively from step 1 to 5, the active load of the wind farm for one load is constant, and the apparent power for one load of the wind farm also increases in steps of 5 i.e. from step 1 to 5. The percentage rate of increase of generation and using of reactive power is graphically represented in Fig. 15. The rate increase of reactive power generation from wind farm, rate increase of apparent power for one load and the rate increase of reactive power for one load experiences a progressive rise as we move from step 1 to step 5. Thus, from Table 2, and Fig. 15, It will be the same steps for other loads that is L1 = L2 = L3. It can be deduce that reactive power is used to maintain voltage level so that active power can flow to do useful work in an electric power distribution system. Suppose the proposed wind energy distribution system is a weak network with a large reactive load. If we suddenly disconnect the load, we will encounter a peak in the voltage. The systems active power will be utilized to do beneficial task. It is observed that apparent power which is a combination of reactive and active power without reference to phase angle progressively rises, meaning that the wind farm has infused reactive power in order to control and manage the voltage profile of our proposed network. The sending active power at the beginning of lines (P_s), the receiving active power at the end of lines (P_r), the voltage level at the beginning of the lines (U_s), and the voltage level at the end of lines (U_r) where measured in order to determine; Firstly, the power losses (ΔP) of the lines and secondly, the voltage drop (ΔV) on the lines. The measured values of sending and receiving active power, and sending and receiving voltage of lines 1, 2, and 3 for the various steps of the wind farm and loads is shown in Table 2. Also, the sending and receiving active power of the lines is displayed in Fig. 16,*a*,*b*.

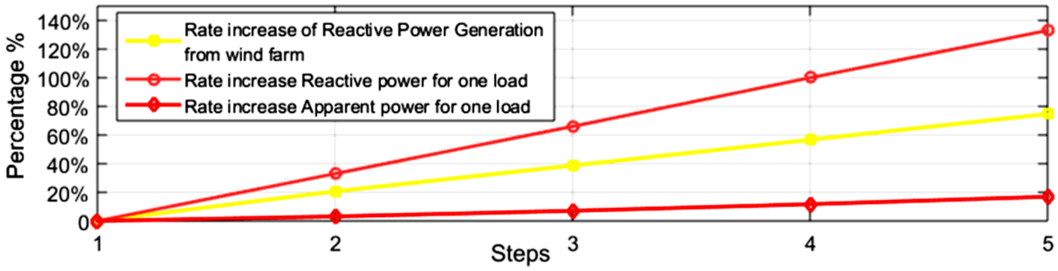
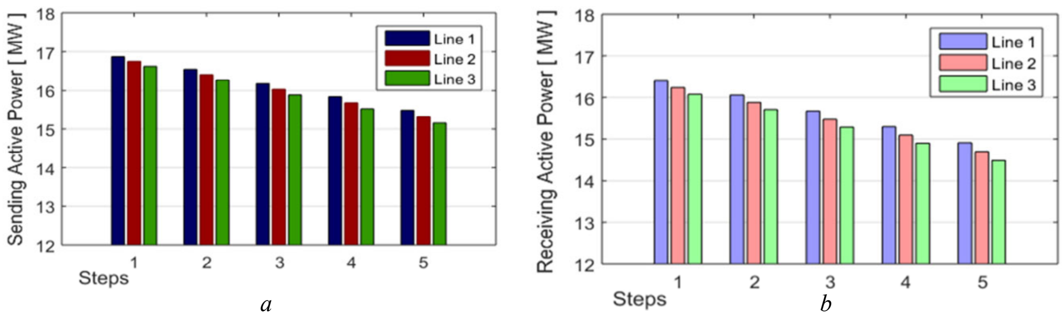


Fig. 15. Percentage rate increase for generation and using of reactive power



a *b*

Fig. 16. Sending (*a*) and receiving (*b*) active power of lines

For step 1 to 5 observed, the sending and receiving active power decreases for line 1, 2, and 3 respectively. The diagrams in Fig. 16 show that for each step observed active power losses decreases. While the voltage difference increases from line 1 to line 3 respectively, all these is depicted in Table 1, 2 and Fig. 15.

Therefore, we can say that power losses have been reduced on the electric power distribution system as a result of reactive power compensation near the loads by the wind farm. Considering only the resistive losses in the distribution circuit, and remembering that power losses is directly in proportion to the square of the immensity of the current flow on the line, it is simple to notice that the power losses in one line will rise remarkably more than the decrease of power losses in other different power distribution lines. This demonstrates that a straightforward method to reduce the total losses is to sustain a stable rise in voltage. Here, Fig. 17 depicts that power losses on the lines increases as we move from step 1 to 5, insinuating that the power produced in substation passes from one end to another from complex systems to the end users. It is a fact that the unit of electric power entered by substation usually does not match with the units allocated to the end users. Several percentages of the components are lost in the wind farm electric power distribution system. Figure 18 depicts the percentage voltage on the ref. 66 kV line substation within the range of + or – 10 %, at the ends of lines 1, 2, and 3, that is voltage receiving ends of lines 1, 2, and 3. It is discovered that there is % decrease of voltage ref. 66 kV for line 1 and 2 as we move from step 5 to step 1, but line 3 experiences not too significant change, but only a slight increase as we move from step 5 to step 1. Meaning that the distribution voltage is regulated owing to the wind farm distribution systems ability to supply close to steady voltage over a broad choice of load situations. The diagram in Fig. 19 illustrates the percentage change in voltage and power losses on the lines, and increase of reactive load, and reactive power generation of wind farm. It shows that the listed parameters in i.e. % change in voltage, power losses on lines, increase of reactive power and reactive power generation of the wind farm gradually increases from negative to positive values, from step 1 to 5 of the lines observed. Meaning that the wind farm connected distribution power system is able to produce and control reactive power according to the usage of reactive loads.

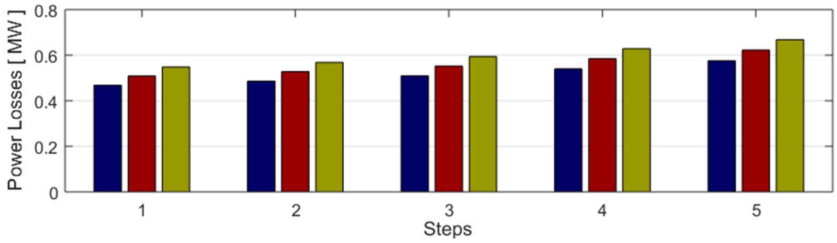


Fig. 17. Power losses of lines

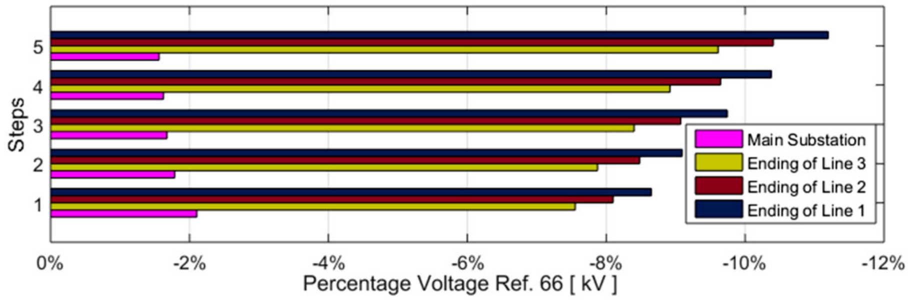


Fig. 18. Percentage voltage ref. 66 kV of lines

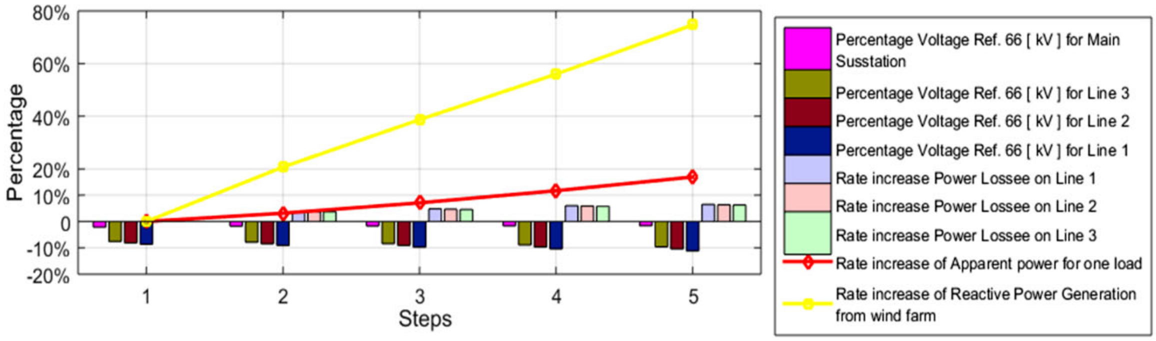


Fig. 19. Percentage change in voltage and power losses of lines, and the increase of reactive load, and reactive power generation of wind farm

Table 1

Measured values of Q_{ref}, active and reactive power of the wind farm

Step	Q_{ref}, p.u.	Rate increase, % Q_{ref}	Reactive power Q_G , MVAr	Active power P_G, MW	Wind farm mode	Speed, m/s
1	0	0 %	0	0	OFF	0
2	0.207	20.7 %	6.941	30	ON	15
3	0.387	38.7 %	12.96	30	ON	15
4	0.567	56 %	19.2	30	ON	15
5	0.747	74.7 %	23.81	30	ON	15

Table 2

Measured values of reactive, active and apparent power of one load

Step	Rate increase, % Q_L	Reactive load Q_L MVAr	Active load P_L, MW	Apparent load S_L, MVA	Rate increase, % S_L	Wind farm mode	Q_{ref}, p.u.
1	0 %	6	20	20.88	0 %	OFF	0
2	33 %	8	20	21.54	3.161 %	ON	0.207
3	66 %	10	20	22.36	7.089 %	ON	0.387
4	100 %	12	20	23.324	11.704 %	ON	0.567
5	133 %	14	20	24.413	16.92 %	ON	0.747

Conclusions.

The theme of this research paper centres on the design and analysis of the whole control arrangement of a variable speed wind turbine with multi-pole PMSG. Owing to the gearless structure and the permanent magnet excitation of the synchronous generator, it symbolizes an utmost effective and inexpensive or economical maintenance way out, which will be extremely advantageous in offshore wind turbine applications. A complete effectual simulation model is established in the

MATLAB/Simulink software environment. The control of the wind turbine is realized by utilizing the power converter control in harmonization with the pitch control plan. The converter control is an assurance for the variable speed operation to obtain the most favourable power performance. When wind speed is elevated than the rated speed, the pitch angle control operation alters the blade incidence so that the output power of the generator is within the permitted limits. MATLAB/Simulink simulations reveal that the control technique triumphantly controls the variable speed PMSG wind turbine within the limit of standard functional circumstances. The control scheme enables the independent control of active and reactive power according to applied reference values at variable speed. Hence, the proposed gearless wind power plants utilizing the synchronous generator with permanent magnets allows the production of power at variable speeds attaining stability during various wind speed operational points investigated. The rotor coordinate system of the generator allows the control of the synchronous generator magnetic flow and torque separately. The results of this research are an indication of a robust control circuit functionality and stability of the whole activity of the proposed scheme. It can consequently be deduced, that the gearless variable-speed wind turbine PMSG can function in the same way as the traditional wind power plants. The results obtained from the (3·10 MW = 30 MW) wind farm scheme case study agree with other studies carried out worldwide regarding active and reactive power control in MV distribution network connected to wind farm with IGBT power electronics converters as the schemes simulation results reveals an enhanced voltage profile and reduction in power losses.

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Conflict of interest. The authors declare that they have no conflicts of interest.

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