Turkish Journal of Electromechanics and Energy
ISSN: 2547-975X
Vol:6, No:2, Page 64-72 (2021)
https://www.scienceliterature.com

Investigation of vertical axis wind turbines and the design of their components

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ARTICLE INFO

***Article Type*:**
Invited Article [c]

Article History:
Received: 15 April 2021
Revised: 6 August 2021
Accepted: 9 August 2021
Published: 25 September 2021

Editor of the Article:
Y. Soufi

Keywords:
Wind turbine, Vertical axis wind turbine
Axial flux permanent magnet generator
Buck-boost converter, PID controller

ABSTRACT

Wind energy and developments of wind turbine design are getting important today all around the world. To increase the efficiency of wind turbines, scientists have done many kinds of research. One of these topics to increase efficiency is vertical axis wind turbines, blades, and generators design. Also, the generated energy and connection to the grid are causes some problems and have to study.
In this study, vertical axis wind turbine blades and developments to increase efficiency are investigated firstly. This paper studies the design steps and magnetic equation of an axial flux, permanent magnets, coreless stator, and rotor designed for a small wind turbine application. Stator voltages depending on the magnetic flux distribution have been obtained for different operating speeds and load conditions. The stator voltages for the three-phase are rectified and connected to a buck-boost converter to regulate bus voltage. The buck-boost converter is controlled with a proportional integral derivative (PID) controller for the desired output voltage. The electricity is connected to the grid, or a direct current (DC) bus is investigated and given a proposal with power electronic converters and simulated with MATLAB/Simulink. Moreover, the model is analysed for inrush open circuit input voltage and short circuit load conditions for 0.5 second time intervals.

Cite this article: A. Boztaş, O. Demirbaş, M. E. Şahin, "Investigation of vertical axis wind turbines and the design of their components" *Turkish Journal of Electromechanics & Energy*, 6(2), pp.64-72, 2021.

1. INTRODUCTION

In our world, where the need for energy is increasing, the interest in renewable energy sources is rising day by day. Among these sources, wind energy attracts the most attention after solar energy. The turbines used to convert wind energy into electrical energy can be produced with a gear system or directly connected. These systems are need overhaul, additional costs, and generates noise even with low-speed power generation with geared wind turbines [1].

The high coercivity and low permeability properties of hard magnetic materials make it difficult to magnetise and demagnetise. These materials are called permanent magnets because they are magnetised once and then retain their magnetisation for a long time [2]. With the emergence of NdFeB magnets in the 1980s, permanent magnet machine technology gained high momentum. Today, permanent magnet machines are used in many fields, from electric vehicles to the space industry. One of these areas is wind energy systems. Losses are reduced by using magnets for excitation, and the efficiency of the system increases [3, 4].

Permanent magnet machines are used for all the energy conversion devices where a magnet makes the magnetic excitation [5]. High-density magnetic materials are now widely used in both motor applications and generator applications. Depending on the magnetic flux situation, permanent magnet machines are examined in two main sections, radial and axial. Depending on the rotor position, different versions of both structures may be used in wind turbine applications [6]. The axial flux permanent magnet (AFPM) machine, also called a disc type, is more suitable for wind turbines due to its structural feature. In wind generator applications, axial flux permanent magnet generators with corrugated cores in the stator can also be used [7]. However, a coreless stator and surface-mounted axial flux machine eliminate the yield and hysteresis current losses.

The generator output voltage is not stable, and the DC voltage supplies a load quickly. There are required components to adjust the output voltage to do the desired voltage level [8]. For single-phase or three-phase generators, output voltages are rectified with a full-bridge converter to DC voltage. However, this DC voltage is not stable and constant to supply the loads and batteries [9-12]. So there is a buck-boost DC to DC converter circuit to adjust the output voltage required bus voltage. If the rectifier output voltage is lower than the DC bus voltage depends on the wind speed, the converter works in a boost mode to increase the input voltage. If

[c]Initial version of this article was presented in the 5th International Anatolian Energy Symposium (5th AES) proceedings held on March 24-26, 2021, in Trabzon, TURKEY. It was subjected to a peer-review process before its publications.

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the rectifier output voltage is higher than the DC bus voltage depends on the high wind speeds converter work in a buck mode to decreases the input voltage. However, this converter regulates the output voltages, ripples and fluctuations. This system is proposed for off-grid street lighting with battery energy storage.

In this paper, the investigation of production and analysis of a handmade small power wind turbine that can be a solution option in remote rural areas where electricity is not available is aimed [13]. To connect the generator and on-grid system is required some complex inverter applications [14, 15]. The vertical axis turbines can operate at low wind speeds without the need for any tower also [16]. The Savonius turbine creates a moment in the inner part of the cylinder [17]. Darrieur rotors are highly efficient but difficult to operate. The H rotor Darrieur model was formed by developing the vertical axis Darrieur wind turbine [16]. Many companies apply the experiences of horizontal turbine design to vertical turbines because of the lack of design theories and design basis, and some companies design a vertical turbine based on their preference [18].

The AFPM models can be designed as a single rotor single stator, double rotor single stator (TORUS), single rotor double stator (AFIR), multirotor multi stator, and obtained various topologies [19]. 2-D or 3-D analysis may be preferred when performing the investigation with the finite element method. When studying the BH curves, steel, which is a soft magnetic material, must be specified. Today, the most widely used magnet in permanent magnet machines is the NdFeB magnet. The magnets are mounted in reverse polarity with the magnet on one side when mounting on steel [19, 20]. The proposed vertical axis wind turbine and the components can generate 50 kWh of energy per month for eight battery packs by connecting the rectifier to the generator at an optimum wind speed of 10 km – 36 km/hr [20-22]. The rectified DC voltages are applied to a converter circuit. The converter circuit output voltage is adjusted to the desired voltage using a PID controller. This controller compared the output voltage with the desired reference voltage and obtained a PWM signal to drive the converter to be adjusted the output voltage [23].

It is possible to find some current studies for vertical axis wind turbines in literate focused on some specific problems and solutions. An experimental test on the various dual-rotor systems was conducted in a wind tunnel. A recent study analysed the relationship between solidity and the dual rotor system. The performance of the double rotor system under skewed flow is discussed. The potential of a dual rotor system on the building is studied in various major cities [24]. The V-shaped blade is implemented to improve the power performance of a vertical axis wind turbine in one other study. The mechanisms of dynamic stalling and flow structures are studied carefully [25]. A rhombus deflector was studied to improves the performance of a pair of counter-rotating vertical axis wind turbines. The wind turbine power output increases about 38.6% at low tip speed ratios, and the deflector accelerates flow velocity and restrains flow separation on the blade [26]. A novel vertical axis wind turbine with rotatable auxiliary blades is made, and wind tunnel experiments are carried out for the proposed wind turbine. Constant output power at different wind speeds is realised through pitch control [27]. A study reviews recent research in the wake aerodynamics of H-rotor vertical axis wind turbines. The general mathematical expressions for analysing the rotor aerodynamics of vertical axis wind turbines are presented, followed by a classic aerodynamic model [28].

Wind energy is one of the essential sustainable energies. Still, the distinctive characters of the primary source, which is characterised by a random wind speed variation, make the control process challenging to maximise the power [29]. Some modern control methods are proposed for the maximum power point tracking of variable wind speeds. Optimal control, particle swarm optimisation based sliding mode controls and fuzzy logic controllers are a few implementations of this maximum power point tracking methods [29, 30].

This paper aims to produce and analyse a small power vertical axis wind turbine, which is handmade and can be a solution option in remote rural areas where electricity is unavailable. In the proposed system, the stator windings are fixed to each other after they are formed in desired windings and sizes and embedded in the material created with a mixture of epoxy resin, talcum powder, and hardener. Rotor structures are also embedded in the same mix. Thus, the magnets are protected against structural stresses and corrosion. The generated electricity from the turbine is rectified with a full bridge rectifier. A buck-boost converter is used to increase or decrease these voltages to the desired voltage levels for the batteries' charge. The simulations and design steps are given in this paper as a preliminary study. The general structure of the proposed vertical axis wind turbine and its components are presented in Figure 1 [31]. The details of the installed system are given in section three. The simulation and results of the designed rectifier and converter part are shown in section four.

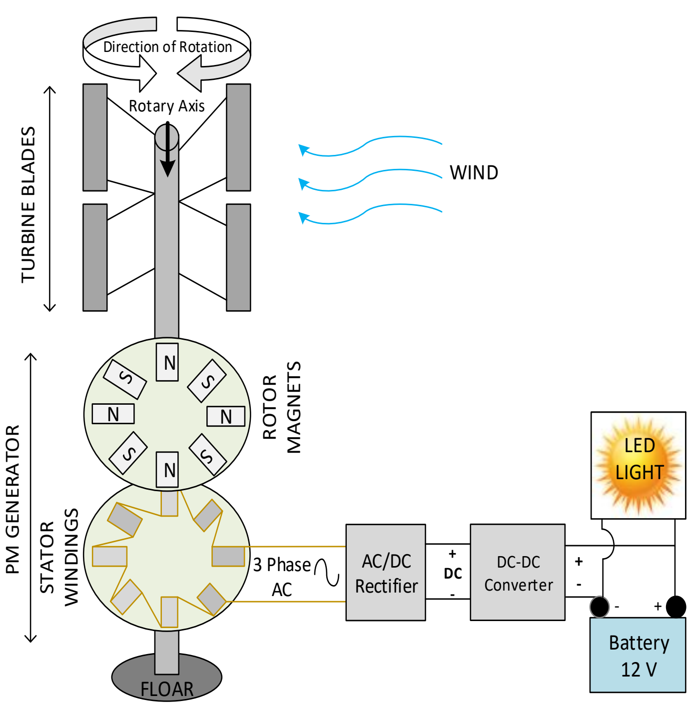


Fig. 1. The general structure of the vertical axis wind turbine and its components.

2. COMPONENTS OF INSTALLED SYSTEM

In this article, the investigation of production and analysis of a handmade small power wind turbine that can be a solution option in remote rural areas where electricity is not available is aimed [13]. The stator windings are fixed in the installed system after they are formed in desired windings and sizes. Rotor structures are also embedded in the same mixture. The magnets are protected against structural stresses and corrosion, and attached rectifier and converter circuits for the DC bus voltage for an off-grid system. To connect the generator and on-grid system is required some complex inverter applications [14, 15]. The following section introduces the components of the system.

2.1. Blades

The rotation axis of the vertical axis wind turbine systems is perpendicular to the direction of the wind. Thus, these turbines can take the wind from all ways and generate electricity by rotating accordingly. For this reason, it has an advantage compared to horizontal axis wind turbines. It is less efficient than horizontal axis turbines in terms of efficiency, and the efficiency of these turbines, which lift the wind by dragging, is approximately 35%. These turbines can operate at low wind speeds without the need for any tower also [16].

Three basic types of vertical axis wind turbine models are given in Figure 2. The Savonius turbine creates a moment in the inner part of the cylinder with the wind effect coming in any direction while it makes a negative moment in the outer part of the cylinder, and thus it rotates [17]. Darrieur rotors are highly efficient but difficult to operate. The H rotor Darrieur model was formed by developing the vertical axis Darrieur wind turbine and replaced by the curved rotor blades in the Darrieur wind turbine are the smooth aerodynamic profile and the application of pitch control to the blades [16]. Many companies apply the experiences of horizontal turbine design to vertical turbines because of the lack of design theories and design basis, and some companies design a vertical turbine based on their preference [18].

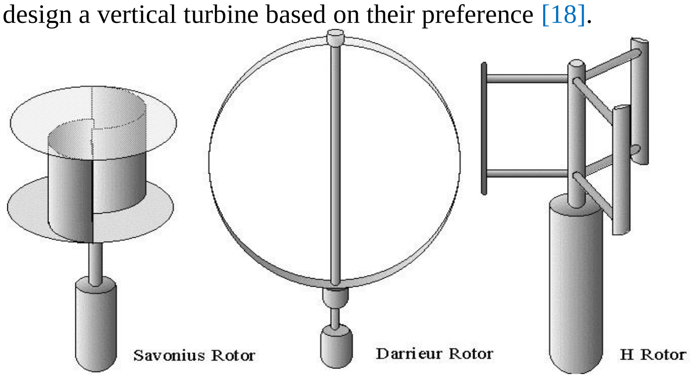


Fig. 2. Three types of vertical axis wind turbine models [18].

2.2. Generator Part

The Axial Flux Permanent Magnet (AFPM) machine model is shown in Figure 3(a). Disc-type rotors in the machine consist of permanent magnets placed on steel. An equal number of permanent magnets in both rotors must have reverse polarity with the magnet placed on the opposite rotor steel in the same position and with the magnet next to it on the same steel. Thus, magnets, air gaps, stator windings, and rotor as a closed magnetic circuit are obtained through the steel [12]. The distribution of magnetic fields in a coreless axial flux machine is shown in Figure 3(b). These AFPM models can be designed as a single rotor single stator, double rotor single stator (TORUS), single rotor double stator (AFIR), multirotor multi stator, and obtained various topologies [19].

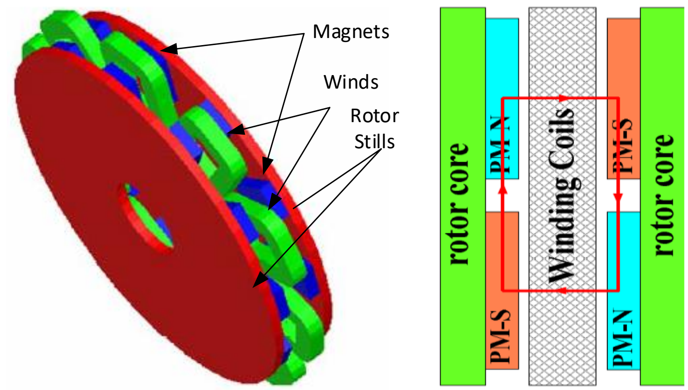


Fig. 3. Coreless EASM model (a), Cross section and distribution of magnetic field (b) [12, 19].

The finite element method used in magnetic field analysis utilises Maxwell's equations, as seen in Equation 1 [8]. The application of the finite element method to the design of electrical machines allows the determination of important design parameters such as; flux bond, induced voltages, core losses, winding inductances, and magnetic moment with very high accuracy [11, 12].

$$\emptyset = \int_s B.dS \rightarrow e(t) = N.\frac{d\emptyset}{dt} \rightarrow e(t) = N.\frac{d\emptyset}{d\theta}.\frac{d\theta}{dt} \quad (1)$$

The change of the rotor position with time will give the angular velocity, and the voltage expression can be written as is seen in Equation 2. The number of windings (N), Angular velocity (*w*), Air gap magnetic flux (Øg), Rotor angular position (θ) are the parameters in this equation.

$$e(t) = N.w.\frac{d\emptyset g}{d\theta} \quad (2)$$

2-D or 3-D analysis may be preferred when performing the investigation with the finite element method. In the 2-D analysis, it is possible to reach the approximate result in a shorter time; *2-D* analysis does not process the entire radial and axial geometry and cannot accurately calculate flux distributions on the structure. In the 3-D analysis, almost exactly the correct result is achieved slightly longer [19].

The windings must be appropriately positioned so that the windings make the best use of the magnetic field generated by the magnets. The induced winding voltages are sinusoidal, and the phase difference between the winding voltages is the same. Figure 4 shows the windings diagram and the position of the windings.

If the magnetic property of the materials can quickly deteriorate, such materials are called soft magnetic materials [3]. When performing the analysis of the *BH* curves, steel, which is a soft magnetic material, must be specified. Today, the most widely used magnet in permanent magnet machines is the *NdFeB* magnet. In the axial flux machine produced, 12 magnets on rotor steel are uniformly spaced. The magnets are mounted in reverse polarity with the magnet on one side when mounting on steel [19, 20]. Figure 4 shows one of the rotor discs plotted in cad software.

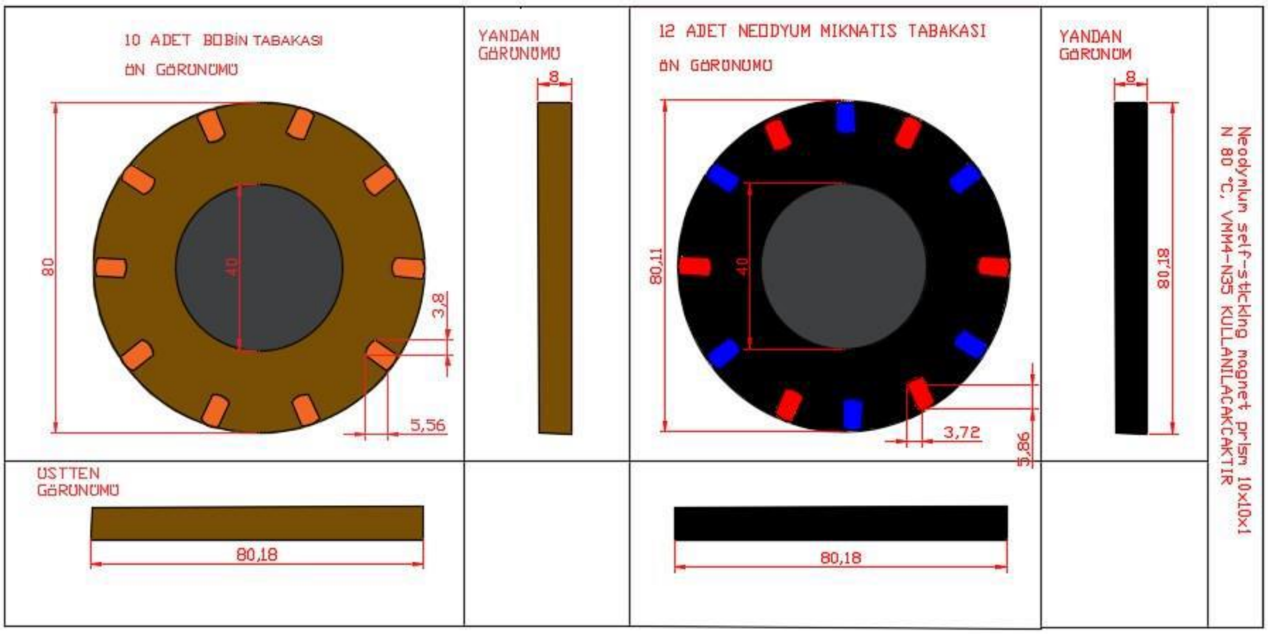


Fig. 4. The winding diagram and the position of the magnets on the rotor disk.

For the blades, it utilises a primary component of plastics or plywood. It is in connection with rods having a cover of sturdy aluminium. There are two separate steel discs with magnets on them for the alternator. On the other hand, copper wires are fixed to the main shaft around their axis. The proposed vertical axis wind turbine and the components are shown in Figure 5. This single component can generate 50 kWh of energy per month for eight battery packs by connecting the rectifier to the generator at an optimum wind speed of 10 km – 36 km/hr [20-22].

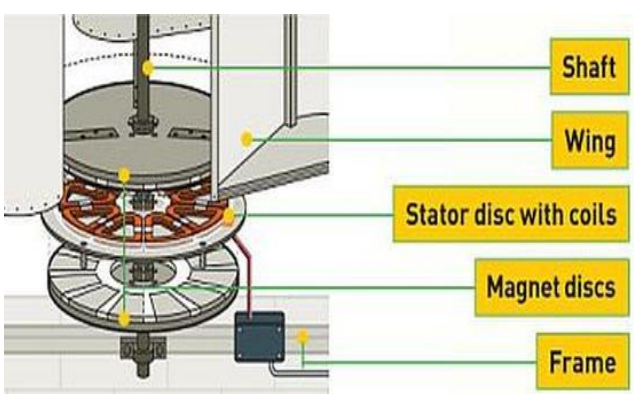
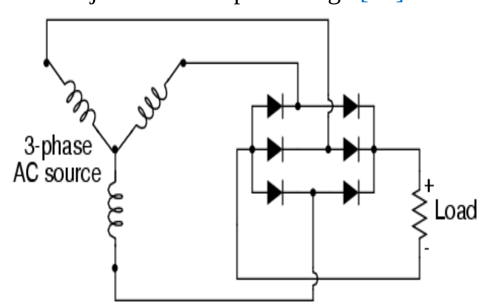


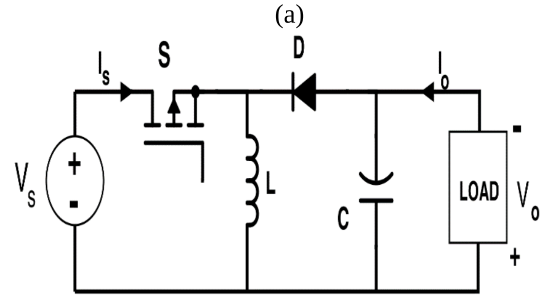
Fig. 5. The constructed vertical axis wind turbine and the components [21].

2.3 Rectifier and Converter

The obtained voltages from the wind turbines are applied to a rectifier circuit to rectify the DC voltages. There is used a three-phase rectifier circuit to convert the three-phase AC voltages to DC voltages. The rectifier circuit is shown in Figure 6 (a). The rectified DC voltages are applied to a converter circuit. This converter is selected as a buck-boost converter to increase or decrease the input voltages. The DC to DC buck-boost converter circuit is given in Figure 6 (b). The converter circuit output voltage is adjusted to the desired voltage using a PID controller. This controller compared the output voltage with the desired reference voltage and obtained a PWM signal to drive the converter to be adjusted the output voltage [23].



(a)



(b)

Fig. 6. (a) Three-phase rectifier circuit, (b) The DC-DC buck-boost converter.

3. SIMULATIONS AND RESULTS

The proposed AFPM wind system electrical part is simulated in MATLAB/Simulink and shown in Figure 8. The AFPM accepted a three-phase AC source, and the voltage is changed from 0 to 50 V. The first block in Figure 8 shows the three-phase wind turbine sources and rectifier circuit consisting of six diodes. The rectified single-phase voltage is applied to the buck-boost converter circuit. The PID controller controls the converter output voltage, which compares with a reference voltage and output voltage as an error signal. This error signal is applied to the PID controller, and the obtained error amplifier signal is compared to a high frequency sawtooth to generate the PWM switching signal. The PWM switching signal drives the buck-boost converter MOSFET switching component. If the duty ratio of the PWM signal is less than 50%, the converter works as a buck converter. If the PWM signal is more than 50%, the converter works as a boost converter. This converter is controlled by the PID controller adjusting the converter parameters. The PID controller drives the error signal to obtain an amplified error signal and the PWM signal. The general equation of the PID controller is given in Equation 3. The $K_P=0.02$, $Ki=0.5$ and $K_d=0$ were selected for this equation, and it converts a PI controller.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{d(t)} \quad (3)$$

The general block diagram of the converter with the PI controller is shown in Figure 7. The error signal is obtained from the difference of output and reference voltage applied to the PI controller to implement the PWM process for generating the switching signal. The control signal compared a high-frequency sawtooth signal to obtain the switching password [23].

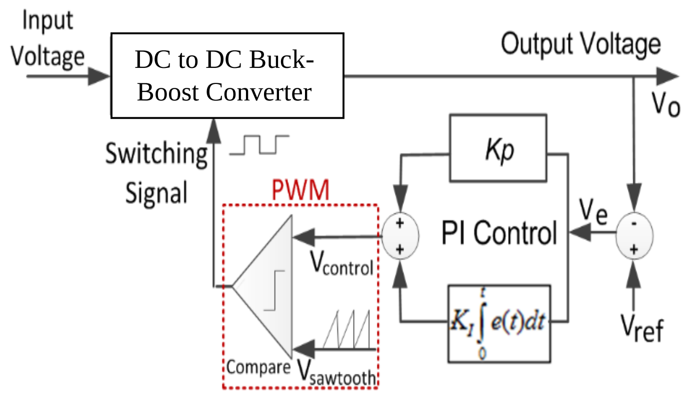


Fig. 7. Block diagram of the DC-DC converter with a PI controller [23].

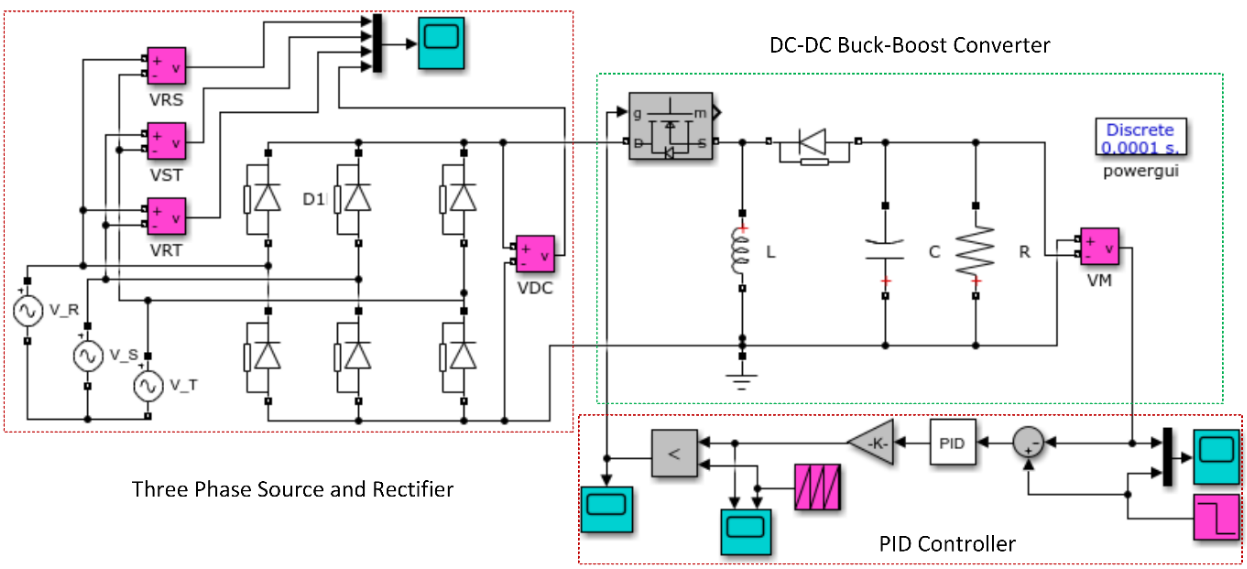
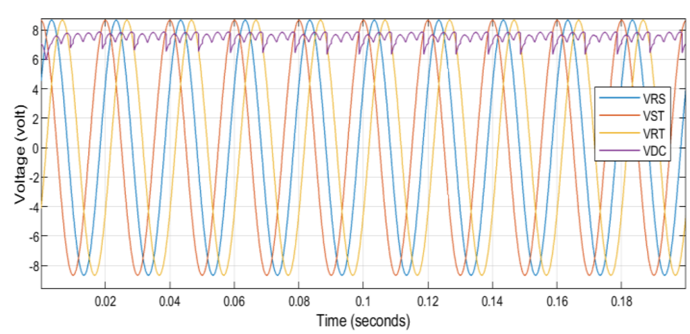
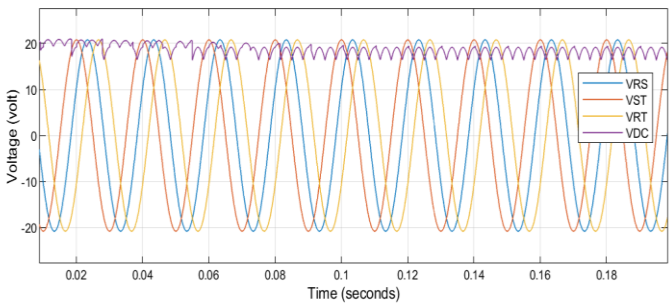


Fig. 8. Simulation model of the total system.

The simulation results for three-phase to phase inputs (V_{RS}, V_{ST}, V_{RT}) and three-phase rectifier outputs (V_{DC}) are for different input voltages are shown in Figure 8. Figure 9 (a, b, c) shows the three input voltages for 5 V, 12 V, 30 V maximum phase voltage, and rectifier output voltage. The rectifier output voltages are near the phase to phase maximum voltage with small voltage drops (~1.4 V) on diodes. So the rectifier output voltages nearly 8 V, 19 V, and 50 V with small ripples. These ripples are depending on the load power.



(a)



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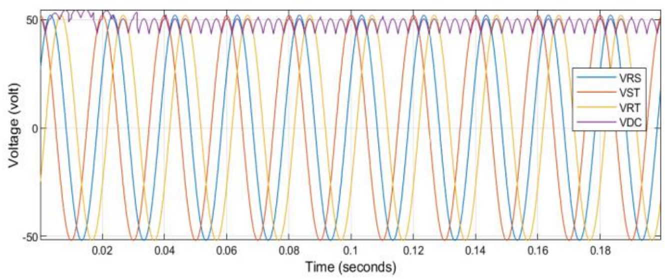
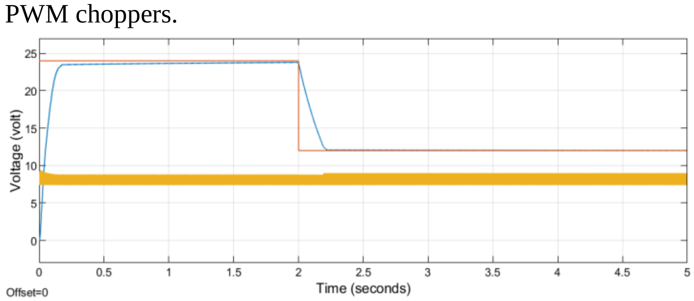


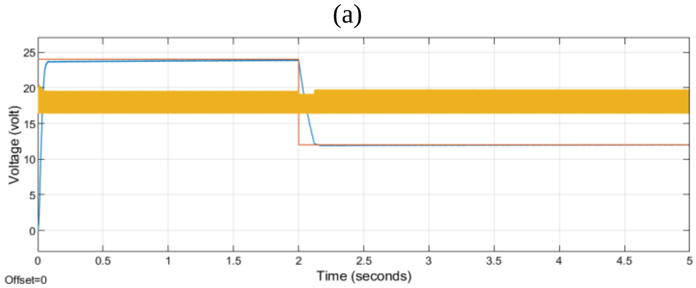
(c)

Fig. 9. Three input voltage for (a) 5V, (b) 12 V, (c) 30 V maximum phase and rectifier output voltages.

The simulation results for rectified input voltages (8 V, 19 V, 50 V) are shown in Figure 10 (a, b, c). The converter output voltage variations are given for 12 V and 24 V reference voltage depending on the different battery connections. For 8 V input voltage and 10 Ω load resistance, for 19 V input voltage and 6 Ω load resistance, for 50 V input voltage and 6 Ω load resistance output voltages are given in Figure 10 (a, b, c) respectively. There are some ripples depend on the output voltage. However, they are under the expectable levels. Also, the waves on the rectified voltage are eliminated by the buck-boost converter. Also, the rectified voltage can be adjusted to desired voltage levels by the buck-boost converter forever conditions. It is not possible with the PWM choppers.



(a)



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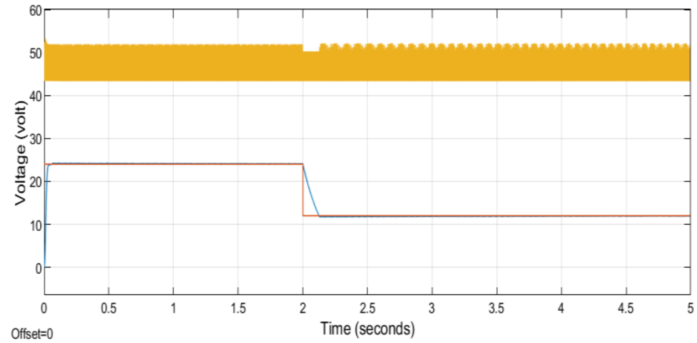


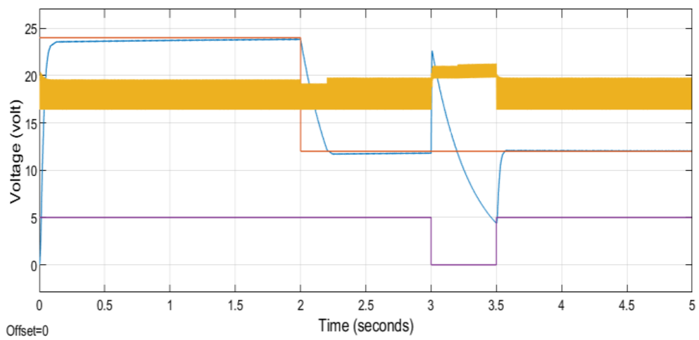
(c)

Fig. 10. The simulation results for rectified input voltages (a) 8V, (b) 19V, (c) 50V and for different references (12V, 24V).

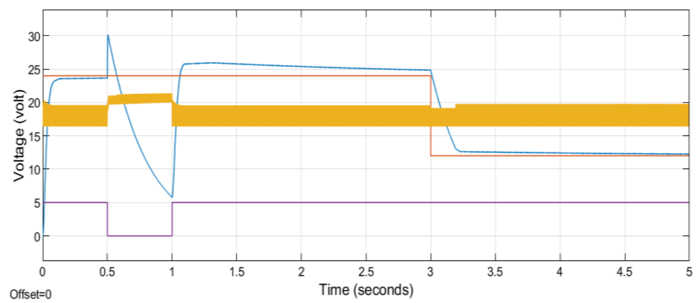
The simulation results show that different input voltages (5 V, 12 V, 30 V) depend on different wind speeds are rectified to DC voltages nearly in maximum values (8V, 19V, 30V of input signals. The buck-boost converter and PID controllers can reduce or enlarge these DC voltages to the desired voltage levels. The controller works as expected, and the results catch the desired reference values with small ripples. These reference values are selected 12 V and 24 V in simulations for the different bus voltages. There is no significant overshoot and error signal. The output signals catch the references with a short time response. Also, it can care the output voltage of the converter is reverse with input voltage.

The previous simulation results are seen for the normal condition of the wind energy system. However, it is not so every time. Sometimes the wind energy can be interrupted, and the turbine cannot work in continuous mode. For these inrush conditions, the model is simulated and observed. The simulation model is tried for 12 V input voltage rectified 19 V maximum voltage in the converter input. These parameters are selected to work the converter in a buck-boost mode for different references, as shown in Figure 11 (a, b). The converter input is made open circuit during the 3 to 3.5 second as shown in Figure 11 (a) the switching signal. The converter works in buck mode and reduces the input voltage to the desired reference voltage. During this time interval, there are some instantaneous changes to the output and input voltage of the converter.

At last, the output voltage is catching the reference quickly and works stable. The converter input is made open circuit during the 0.5 to 1 second as shown in Figure 11 (b) the switching signal. The converter works in boost mode and increases the input voltage to the desired reference voltage. Similarly, there are some changes to the input and out voltages of the converter. At last, the output voltage catches the references with a slight overshoot and delay and works stable.



(a)

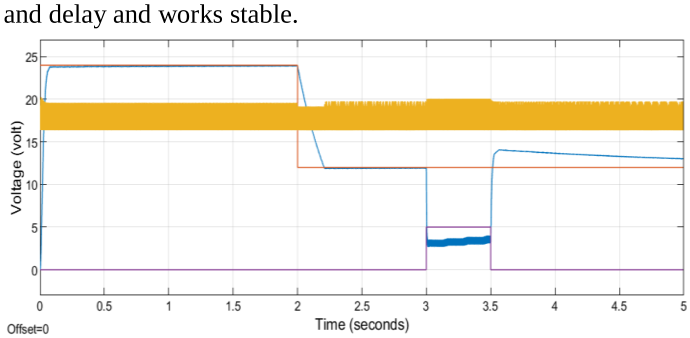


(b)

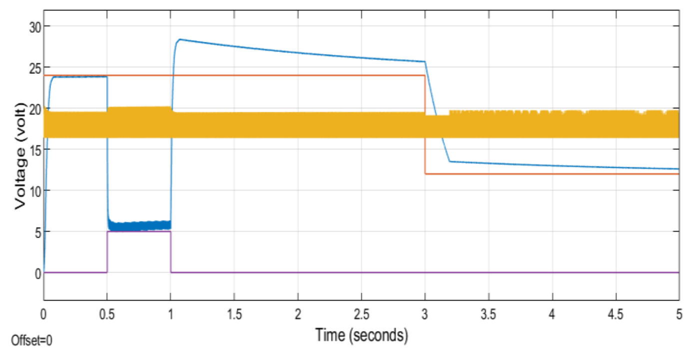
Fig. 11. The simulation results for the open circuit inrush conditions. (a) Buck mode for 12 V input and open circuit during the 3 to 3.5 second, (b) Boost mode for 12 V input and open circuit during the 0.5 to 1 second.

The simulation model is tried for 12 V input voltage rectified 19 V maximum voltage in the converter input for short circuit output conditions. These parameters are selected to work the converter in a buck-boost mode for different references, as shown in Figure 12 (a, b). The converter output is made short circuit during the 3 to 3.5 second as shown in Figure 12 (a) the switching signal. The converter works in buck mode and reduces the input voltage to the desired reference voltage. During this time interval, there are some instantaneous changes to the output and input voltage of the converter.

At last, the output voltage is catching the reference quickly and works stable. The converter output is made short circuit during the 0.5 to 1 second as shown in Figure 12 (b) the switching signal. The converter works in boost mode and increases the input voltage to the desired reference voltage. Similarly, there are some changes to the input and output voltages of the converter. At last, the output voltage catches the references with a slight overshoot and delay and works stable.



(a)



(b)

Fig. 12. The simulation results for the short circuit inrush conditions. (a) Buck mode for 12 V input and open circuit during the 3 to 3.5 second, (b) Boost mode for 12 V input and short circuit during the 0.5 to 1 second.

Table 1. All the simulation parameters of the designed system.

Parameters	*Values*
Phase voltages (V_R=V_S =V_T)	V_{R,S,T_max} = 5V, 12 V, 30 V
Phase to phase voltages (V_{RS}, V_{ST}, V_{RT})	V_{RS,ST,TR_max} = 8V, 19 V, 50 V
Load resistance (R)	R=6 Ω and 10 Ω
Output reference voltages (VR)	V_R=12 V, 24 V
Output power for R=6 Ω, V_R=12V, 24 V	P_{max_24}= 100 W, P_{max}_12=25 W
Inductance value (L)	1,5 mH
Capacitor value (C)	30 mF
Switching components	MOSFETs
Rectifier components	Power diodes
Controller Parameters (PID)	K_P=0.02, K_I=0.5, K_D=0

4. CONCLUSION

The AFPM generator and a power converter system to design a wind energy system is used in this paper. The AFPM generator specifications, design steps, and the other components were also explained in this study. The rectifier and converter parts were used to obtained DC voltage at the desired levels. The generator was assumed to generate 0-30 V three-phase AC voltages; the rectifier and converter parts were designed and simulated in MATLAB/Simulink. The simulation results are obtained for rectifier output voltage and buck-boost converter outputs using different input voltages and output reference voltages with a PI controller. The simulation results give the expected values with small ripples and response time without a high overshoot and long smoothing. Also, the model is analysed for inrush open circuit input voltage and short circuit load conditions for 0.5 second time intervals, and the results are suitable for a stable system. These results show that the power converter and rectifier part can regulate the irregular input voltages depending on the variable wind speeds. Also, the axial axis permanent magnet generator design principles are given in this paper. The authors aim to perform this proposed system experimentally to be used in lightening using power LEDs and batteries without the grid as a future study.

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