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Research Article

Maximum Power Control and Optimization of Switched Reluctance Generators for Wind Turbines

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ABSTRACT

In this paper, a maximum power control and optimization of a 4-phase 8/6-pole Switched Reluctance Generator (SRG) are realized for a wind energy conversion system by using MATLAB/Simulink. Unlike conventional generators, using of the SRGs has increased in variable speed wind turbines due to important advantages such as lower copper losses, simple structure, flexible control, and a good performance in a wide speed range. However, since SRGs work with switching logic, their torque production is fluctuating and optimum turn-on/turn-off angles of the phases must be determined to work as a generator. Therefore, in this study, these angles are optimized based on the speed of the SRG and Maximum Power Point Tracking (MPPT) is realized. Besides, a voltage control is provided by keeping the DC bus voltage at the output of the system constant at the desired value with the help of a chopper controlled unloader. The results obtained from the optimized model for variable wind speed conditions are compared with that of the unoptimized model. It is observed that the SRGs can work more stable with a proper optimization method and the power obtained from the system follows the maximum output power.

Introduction

With the rapidly developing technology and increasing world population, the demand for the electrical energy continues to increase day by day. Therefore, renewable energy sources have gained more importance. These can be classified as wind energy, hydroelectric, solar energy, biomass, and geothermal. Today, approximately 30% of the energy consumed worldwide is met by using renewable energy sources, and 17% of this is energy obtained from the wind [1].

In Wind Power Plants (WPP) which have an important share in terms of the energy production, obtaining maximum output power at variable wind speeds is the most important factor in terms of the efficiency. Switched Reluctance Generators (SRG), which have been increasingly used in these power plants, come to the fore with their significant features such as providing flexibility in the control under variable speed conditions and operating in a wide speed range, lower copper losses because of without windings in the rotors, simple structure, flexible control [2-5]. However, torque ripple is occurred in the SRGs due to working as switching logic. Therefore, switching angles of the phases must be set optimally to work as a generator. Determining right optimization techniques will increase the use of the SRGs in the WPPs.

The power of a wind turbine depends on the mass and rotational speed. To obtained the maximum power from the wind turbine, optimal tip speed ratio should be set [3]. Therefore, there are three common MPPT methods in the literature which are Perturb and Observe (P&O), Power Signal Feedback (PSF), and Tip Speed Ratio (TSR). In this paper, TSR method is used. This control method is based on the principle of controlling the shaft speed to maintain the optimum value of the blade tip speed ratio at any wind speed. The reference shaft speed value obtained from the wind speed is compared with the instantaneous shaft speed value and sent to the controller. With the help of the power electronics circuit, the switching process is performed so that the instantaneous shaft speed reaches the required reference shaft speed value.

In the literature, the studies realized on this field are examined in detail. First of all [6] presents an output power optimization method of the SRG for the wind turbine applications. To obtain an optimal power generation, DC bus voltage level and phase voltage switching angles are taken as the control variables. For this reason, a Differential Evolution (DE) algorithm is used to determine the optimal control variables under multiple operating conditions. The proposed method is tested on a SRG prototype. It is observed that the DE algorithm is proper for the optimal power generation. In [7], the performance of a SRG is optimized for variable speed wind generation systems. The parameters of a driver affect the power generation, torque ripples, and the losses. Therefore, optimal parameters of the SRG must be selected for the operation in a wide speed range. These are obtained by minimizing the cost functions in the realized simulations. The simulation results are validated by comparing the experimental results which are obtained from a wind turbine system. In another study [8], the control of an 8/6 pole SRG with four phases is realized. Torque ripple is minimized by using an Artificial Neural Network (ANN) algorithm. Besides, a new MPPT approach is proposed for the SRG by modifying the classical Hill Climb Searching technique. Thanks to this method, Total Harmonic Distortion is also reduced about 1.45% by utilizing a multi-level diode clamped inverter. A control of the SRG used in the wind power systems is carried out for variable speeds in [9, 10]. A simulation and real-time implementation of the SRG driver are realized by using MATLAB/Simulink and DS1103 Ace kit digital signal processor. The phases currents and output voltage curves of the SRG are examined in the simulations. The simulation results are validated by the experimental results. In [11], a maximum power control method is also proposed for the SRGs used in the wind turbines. To increase the efficiency of the SRG, the switching angle is optimized in the simulations. Then, the simulation results are tested on a 3 kw prototype SRG and the presented algorithm is validated by comparing with each other. Authors in [12, 13] examine the performance of the SRG in variable wind generation systems. Two Direct Power Controls (DPC) which are hysteresis of the SRG phase current for low speed and a single pulse of the current for the high speed operation moods are presented. The results of the DPCs are compared with the Sliding Mode (SM) and PI controllers. It is seen that commutation of the DPCs is occurred with a smooth transition and the operation of the SRGs can be a self-excited mode. The design and control of the SRG are explained to obtain maximum output power and decrease the torque ripple in [14-16]. Phase self-inductance, DC bus voltage, shaft speed, and the switching angles are the design and control parameters in the system. The output powers of 1 Hp and 3 kW generators are handled in the simulations. The switching control is realized by using the DPC and hysteresis control methods. By increasing the efficiency and reducing the torque ripple, the simulation results are validated by the experimental studies. In [17], three-phase SRG is developed for the wind power applications. The transient phase current and energy analyses of the SRG are examined. By setting the switching angles, the closed-loop output power control of the SRG is realized based on the fuzzy logic algorithm. The proposed method is tested on a 500 kW SRG prototype. It is observed that this control approach provides a good performance with 2.2% error. In [18-20], maximum power extraction is studied for a SRG used in the wind turbines by controlling the firing angles. In this studies, turn-on and turn-off angles are optimally set by using PSO and PI controller. By this approaches, high efficiency and power, low torque ripple are provided to verify the proposed approach, the simulation results are compared with the experimental results obtained from a prototype SRG.

As seen from the literature, there are many studies in the field of obtaining maximum output power in the WPPs where conventional generators are used. However, the applications where the Switched Reluctance Machines (SRMs) are mostly operated as a motor are placed. Recently, the studies on the operation of the SRMs as a generator and their performance have also started to gain importance. Therefore, in this paper, a study on the WPP using a SRG which has an important share in the renewable energy sources in terms of the generation is realized. The SRG is preferred due to eliminating many disadvantages of traditional generators. An MPPT is carried out using the blade tip speed ratio method for a variable speed wind turbine system with 8/6 poles 4 phase SRG and a rated output power of 745 W. In addition to the significant advantages of the SRGs, there is a drawback which is the torque ripple. To solve this problem, an optimization of the SRG is also realized by determining optimum turn-on and turn-off angles. The results obtained from the optimized system are compared with that of the unoptimized system. It is observed that the optimized system works more stable for different wind speeds and follows the maximum output power with a great accuracy. Contrary to the studies in the literature used a lot of optimization methods such as the DE, SM, PI, DPC, and ANN, the power gain is also examined for different wind speeds by the proposed optimization method in this study. It is observed that the highest power gain is obtained as 35.45% for the 12.5 m/s wind speed. As a result, it has contributed to the literature on the widespread use of the SRGs in the WPPs by operating more efficiently and maximizing the output power of the WPPs produced using the SRG.

The paper consists of seven parts. Firstly, topology, inductance profile, power converter circuit of the SRGs are handled in Section 2. Then, control of the SRGs is defined in Section 3. The characteristics of a wind turbine are explained in Section 4. After that, power optimization and MATLAB/Simulink model of the SRG are carried out in Sections 4 and 5. The simulation results and discussions are given in Section 6. The general conclusions are explained in the last Section 7.

Switched Reluctance Generators

Topology

Switched Reluctance Generators (SRGs) are simple electrical machines since they have a stator and rotor with salient poles and only windings on the stator, there are no windings or permanent magnets on the rotor [21]. Due to significant properties of the SRGs such as simple structure, robustness, low manufacturing and maintenance costs, high performance and working in the variable speed range, they are a proper candidate for the wind applications [22, 23].

Inductance profile of the SRGs

In the SRMs, as the number of the phases increases, the torque ripple decreases. However, this causes rising the number of solid-conductor elements in the driver circuit. Thus, the cost also increases. To determine the direction of the rotation at the time of acceleration and start by itself as a motor, the SRM must have at least three-phase and the number of stator and rotor poles must be different to accelerate. Hence, in this study, an 8/6 pole 4-phase SRG is preferred as a generator as seen in Fig. 1.

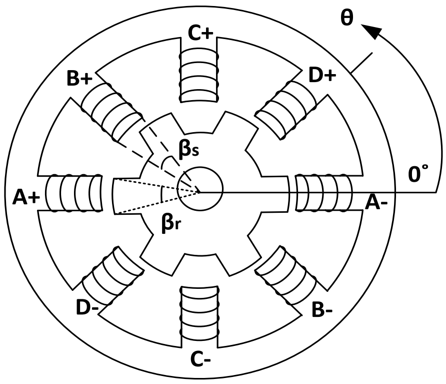

Figure 1. Four-phase 8/6 pole SRG

The variations of the phase inductance for the phase A of an 8/6 pole 4-phase SRG based on the rotor position and the phase currents are shown in Fig. 2.

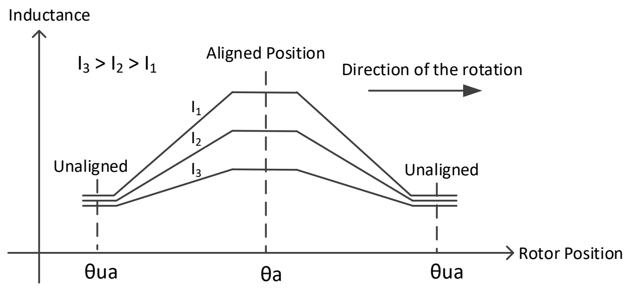

Figure 2. Variation of the phase A inductance of 8/6 pole 4 phase SRG according to the rotor position and phase current

As shown in the Fig. 2, the value of the phase inductance is the minimum in the unaligned position and it is the maximum when it approaches the aligned position. The phase inductance also changes based on the phase current. While the value of the inductance is the highest at the phase current I_1, it is the minimum at the phase current I_3 due to the saturation.

Power converter circuit for the SRG

In the operation of the SRGs, the phases of them must be energized sequentially and a driver must be used to ensure the current flowing from the phases based on the rotor position. In the literature, there are various driver circuits for the control of the SRGs. In this study, an Asymmetric Half Bridge (AHB) converter is preferred as shown in Fig. 3.

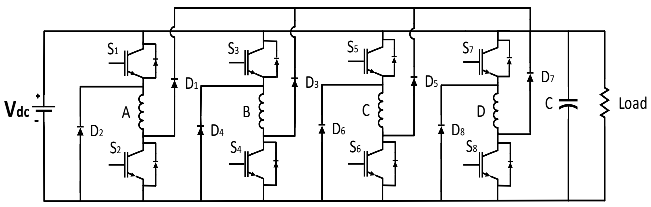

Figure 3. Asymmetric half bridge type converter structure of the 8/6 pole 4-phase SRG

In the AHB circuit, different switching modes of the SRG driver are shown for the phase A in the Fig. 4.

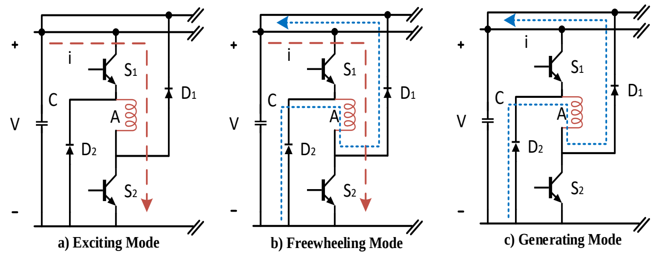

Figure 4. Different switching modes of the SRG driver for the phase A

As seen from the Fig. 4 (a), the exciting mode is a motor operation which is the positive torque region. In this mode, the current flows from the voltage source through the S_1 and S_2 switches and the inductance of the phase A (L_A). D_1 and D_2 diodes are off. In Fig. 4 (b) which is the freewheeling mode, only one of the switches S_1 or S_2 is on and the other is off. This operation mode is used for low and medium speed applications. In Fig. 4 (c) which is the generating mode, both switches S_1 and S_2 are off and the current flows from the D_1 and D_2 diodes and L_A to the voltage source. The value of the inductance reduces and the generator current is produced. Thus, this is the negative torque region.
According to the one phase equivalent circuit of the SRG, the phase voltage can be written as follows

$$V = R.i + \frac{d\psi}{dt} \tag{1}$$

where V, R, i, and ψ are one phase voltage, the phase resistance, phase current, and the magnetic flux, respectively.

The magnetic flux can be explained as follows

$$\psi = L(i,\theta).i \tag{2}$$

When the equation of the phase voltage is rearranged, Equation 7 is obtained as follows

$$V = R.i + L\frac{di}{dt} + i\frac{d\theta}{dt}\frac{dL}{d\theta} \tag{3}$$

where $d\theta/dt$, θ, and L are the rotational speed, the rotor position, and the phase inductance, respectively.

Lastly, the phase voltage is obtained as follows

$$V = R.i + L\frac{di}{dt} + e \tag{4}$$

where e is the back electromotive force.

By neglecting the magnetic saturation, the torque produced by a phase can be defined as follows [22]

$$T_e = \frac{1}{2} i^2 \frac{dL}{d\theta} \tag{5}$$

Control of the SRG

In the controlling of the SRGs, main quantities are the excitation time, operating speed, and excitation voltage. In applications where the load is connected directly to the converter as shown in the Fig. 5, a controlled voltage must be supplied to the load. To keep the generated voltage constant in case of a change in the load, a control system is used by comparing the reference voltage with the load voltage. In this system, the error value obtained from the voltage difference is passed through a PI controller and the reference current value is obtained. Then, this current is compared with the actual phase current value at the output of the machine to keep the phase current at the desired value. The obtained error is controlled by the PI current controller. This method called as the voltage control method is important for some applications such as automotive and aerospace where the DC bus voltage must be kept at a constant value.

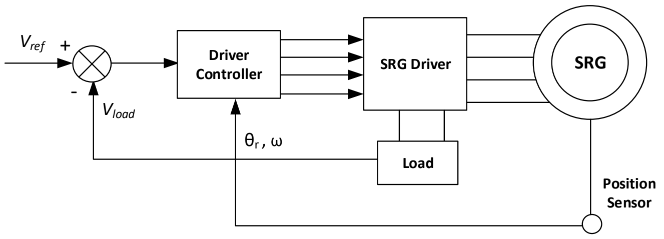

Figure 5. The block diagram of the SRG voltage control method

Besides in the power control method, the power produced by the SRG must be directly controlled. The SRG is connected to the electrical network via DC/AC converter. To implement these control methods, the AHB converter circuit can be activated by three methods which are Pulse Width Modulation (PWM), a current hysteresis regulator and single-pulse operation.

The Characteristics of a Wind Turbine

A wind turbine converts the wind kinetic energy into the mechanical energy with the movement of turbine blades. The mechanical torque T_m applied to the wind turbine shaft can be expressed by [9]

$$T_m = \frac{1}{2} \rho A R \frac{C_p(\lambda)}{\lambda} V_m{}^2 \tag{6}$$

where ρ, A, R, C_p, λ, and V_w are the air density whose value is 1.244 kg/m^3, area swept by the blades, the turbine blade radius, turbine power coefficient, tip speed ratio, and wind speed, respectively.

The wind power can be explained by

$$P_m = \frac{1}{2} \rho\, C_p\, A\, V_r{}^3 \tag{7}$$

The turbine power coefficient is given as follows

$$C_p(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_1} - C_3 \beta - C_4\right) e^{-\left(\frac{C_5}{\lambda_i}\right)} + C_6 \lambda \tag{8}$$

where the parameters indicated by the index C are the design parameters of the turbine and β is the blade pitch angle. C_p is a non-linear function of the blade pitch angle.

The tip speed ratio λ can be calculated as follows

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{9}$$

The variations of the λ and C_p for different β values are shown in Fig. 6.

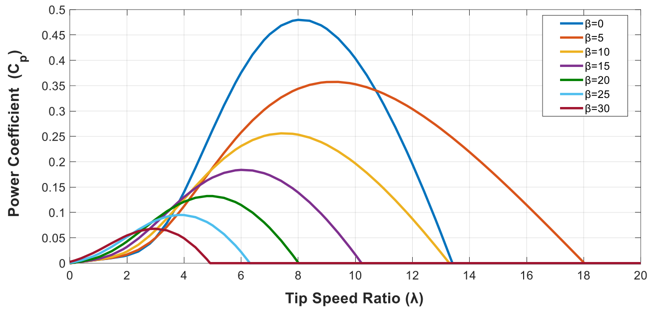

Figure 6. The change of the power coefficient versus the tip speed ratio [23]

It is observed from the Fig. 6 that setting the power coefficient at an appropriate value depends on keeping the β and λ within a certain range. Thus, the design parameters of the turbine are selected as $C_1=0.5176$, $C_2=116$, $C_3=0.4$, $C_4=5$, $C_5=21$, $C_6=0.068$, and $C_{pmax}=0.48$.

In this study, a wind turbine with a nominal output power of 745 W is designed, and R and λ are calculated. Accordingly, the relationship between the turbine speed and output power of the designed wind turbine at different wind speeds is shown in Fig. 7.

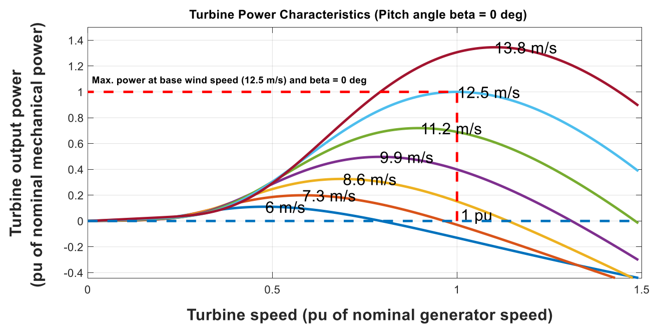

Figure 7. The power characteristics of the designed 745 W wind turbine

As seen from the Fig. 7, the maximum power can be obtained by the turbine speed of 1 pu and the wind speed of 12.5 m/s.

The turbine blade radius can be found by

$$R = \sqrt{\frac{A}{\pi}} \tag{10}$$

Accordingly, the turbine rotor speed can be calculated as follows

$$\omega = \frac{\lambda V_r}{R} \tag{11}$$

The Power Optimization of the SRG

The output power of the SRGs depends on the excitation current, excitation voltage, rotor position, and rotor speed parameters. To increase the efficiency obtained from the SRGs, optimal control of these parameters is required. For this reason, commonly used control methods are the Angle Position Control (APC), Soft-Chopping Current Control (SCCC), and Voltage Chopping Control (VCC). In this study, the APC method is used due to significant advantages which are wide torque setting range, enabling more than one phase to conduct at the same time, and increasing the efficiency by finding the optimum switching angles where minimum torque fluctuation occurs. This method is based on controlling the phase currents by adjusting the turn-on/turn-off angles at the constant voltage applied to the phase winding. Hence, the output power can be adjusted.

MATLAB/Simulink Simulation Model of the SRG used in the Wind Turbine

In this study, a MATLAB/Simulink model of the WPP and optimization of an 8/6 pole 4-phase SRG having 745 W nominal power used in the model are realized. The parameters of the SRG used in the MATLAB/Simulink model are given in Table 1.

Table 1. The parameters of the SRG.

SRG Parameters	Values
Stator Resistance	2.15 Ω
Moment of Inertia	0.004 kg.m^2
Maximum Inductance	250 mH
Minimum Inductance Position	0.5 mH
Rated Current	5 A
Rated Flux Connection	0.3 Vs
Stator Resistance	2.15 Ω
Moment of Inertia	0.004 kg.m^2
Maximum Inductance	250 mH
Minimum Inductance Position	0.5 mH

Initially, the system is designed without using any optimization. Then, MATLAB/Simulink model of a WPP is realized by using an APC optimization method. The results of both systems are given comparatively.

Designed model without using optimization

A MATLAB/Simulink model of the system is created by a simple controller without any optimization. The block diagram of the designed system is given in Fig. 8.

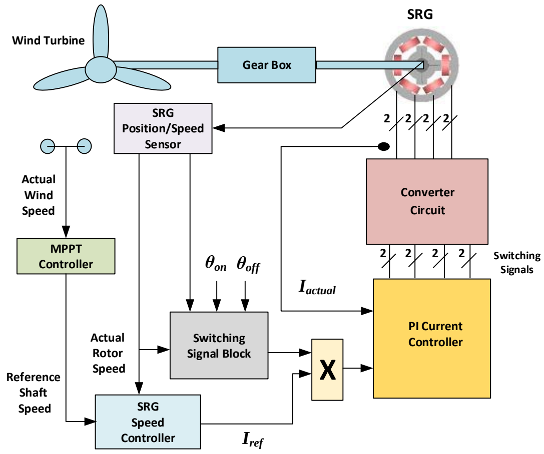

Figure 8. The block diagram of the designed system without using any optimization

In the designed system in the Fig. 8, a MPPT controller and a speed controller blocks are included. The reference speed obtained from the MPPT controller is compared with the actual speed in the speed controller block. The reference current value is obtained by passing a PI control. Then, it is sent to the simpler controller block, where the opening and closing angles are entered manually and the switching signals are generated by obtaining the position information from the SRG speed. A new reference current value is created by multiplying the switching signal and the reference current value. This new reference current is compared with the actual value of the phase current, and the fault current is passed through a relay. After that, the switching signals are generated for the AHB converter at the relay output. These are sent directly to the lower and upper row switches of each phase in the AHB converter.

Designed model with using optimization

In this study, an optimization of the WPP is realized by using the APC method. The block diagram of the designed system is shown in Fig. 9.

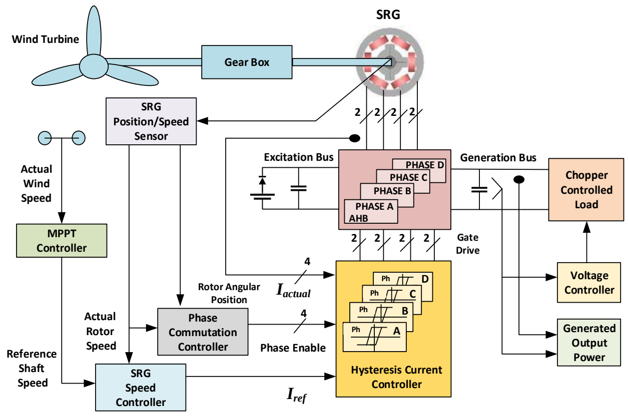

Figure 9. The block diagram of the system designed by the APC method

As shown in the Fig. 9, this APC method that the switching angles change continuously depending on the speed is applied to minimize the torque ripple and keep the phase currents in the desired range. Then, a MATLAB/Simulink model of the system is realized by using the block diagram in Fig. 10.

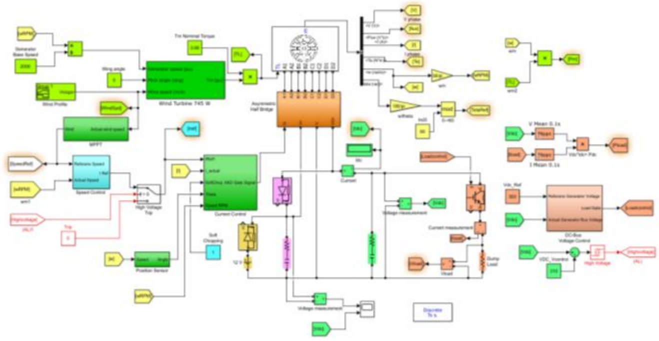

Figure 10. MATLAB/Simulink model of the WPP using an optimization method

In the Fig. 10, the wind speed is first detected by the MPPT controller block and the optimum SRG speed is calculated to obtain the maximum output power. The calculated optimum speed is used by the speed controller block as the reference speed and the speed error is obtained by comparing the actual SRG shaft speed with the reference speed. The speed error is converted to the reference current using a PI control. Then, the reference current is used by the hysteresis current control loop.

Results and Discussions

In this paper, MATLAB/Simulink results of the 8/6 pole 4-phase SRG are obtained for 30 V supply voltage, θ_{on}=15˚ and θ_{off}=30˚, and 1500 rpm SRG speed (157 rad/s). As a result of the simulations, the current, voltage, inductance, and switching signal curves for all phases of the SRG are examined for the optimized and unoptimized systems. In the model, the variations of the wind speeds applied to the turbine inlet of both systems are shown in Fig. 11.

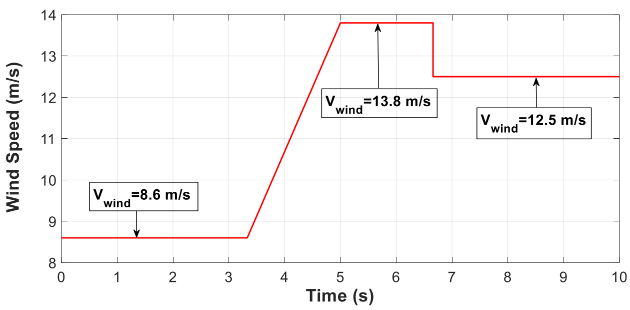

Figure 11. Variation of the wind speeds applied to the entrance of the system

For the wind speeds given in Fig. 11, the SRG shaft speeds which the maximum turbine output power will be obtained are given in Table 2.

Table 2. The SRG speeds required for the MPPT

Wind Speed (m/s)	Turbine Speed for P_{max} (Pu)	Turbine Output Power P_{out} (Pu)	Turbine Output Power P_{out} (W)	SRG Shaft Speed (rpm)
8.6	0.7	0.32	238	1377
12.5	1	1	745	2000
13.8	1.1	1.35	1005	2210

As seen from the Table 2, the wind turbine output power should be 1 pu corresponding to 745 W at a wind speed of 12.5 m/s and the wind turbine shaft speed should be 1 pu corresponding to 2000 rpm. According to these wind speeds, the SRG shaft speed adjusted by the MPPT controller is obtained from the system without and with optimization in Fig. 12 and 13, respectively.

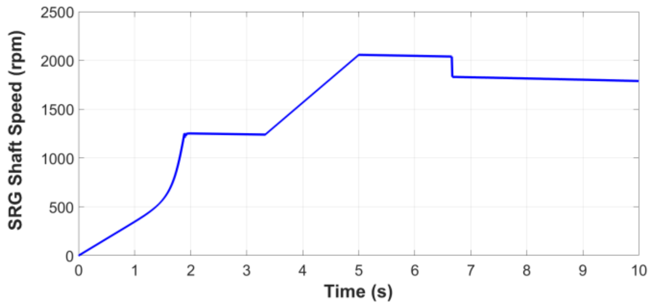

Figure 12. The SRG shaft speed with MPPT controller in the unoptimized system for different wind speeds

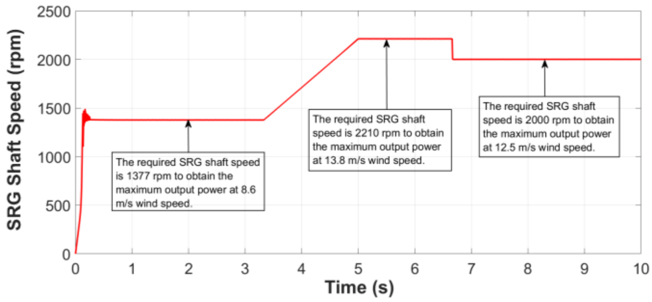

Figure 13. The SRG shaft speed with MPPT controller in the optimized system for different wind speeds

In the system with optimization, it is observed in Fig. 13 that same SRG shaft speed values given in Table 2 are obtained. Initially, a wind speed of 8.6 m/s is applied to the system input for more than 3 s. Accordingly, the shaft speed of the SRG reaches the required shaft speed value which is 1377 rpm for the maximum power in a much shorter time than 1 s while this time is 2 s in the non-optimization system. Besides, the other shaft speed values including 2210 d/d and 2000 d/d, which should be reached for the wind speeds of 13.8 m/s and 12.5 m/s, are also reached quickly in the optimized system. However, in the unoptimized system, the SRG shaft speed moves in a fluctuating manner after catching the reference speed and it has no stability. Under these operating conditions, the turbine maximum output power is drawn for the both systems in Fig. 14 and 15, respectively.

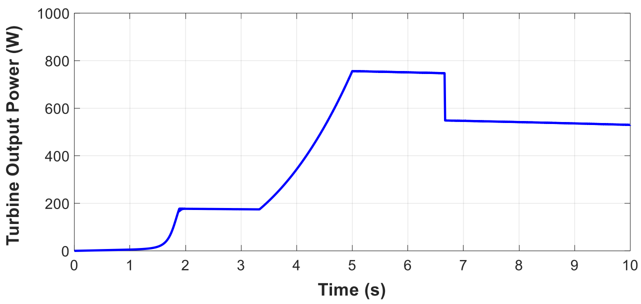

Figure 14. Turbine output power in the unoptimized system for different wind speeds

In the system without optimization in Fig. 14, it is observed that the maximum output power point is followed only at 8.6 m/s wind speed and the system reaches this point in about 2 s, and also the maximum power point values could not be reached for other applied wind speeds.

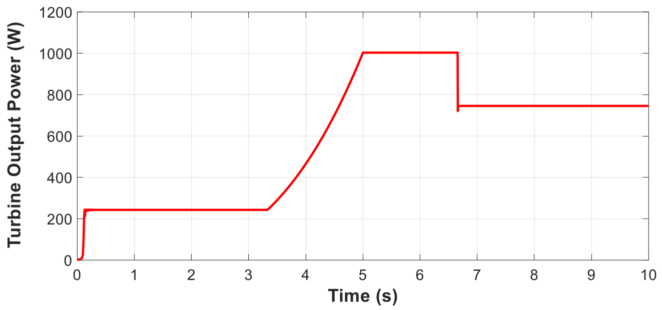

Figure 15. Turbine output power in the optimized system for different wind speeds

In the system with optimization in Fig. 15, 238 W, 745 W and 1005 W output powers are obtained for 6.8 m/s, 13.8 m/s and 12.5 m/s wind speeds applied to the system input, respectively. Furthermore, the turbine output power reaches the first maximum power point of 238 W in less than 1 s.

Under these operating conditions, the variations of the electromagnetic torque (T_e) and DC bus voltage are given for two systems which are unoptimized and optimized in Fig. 16, 17, 18, and 19, respectively.

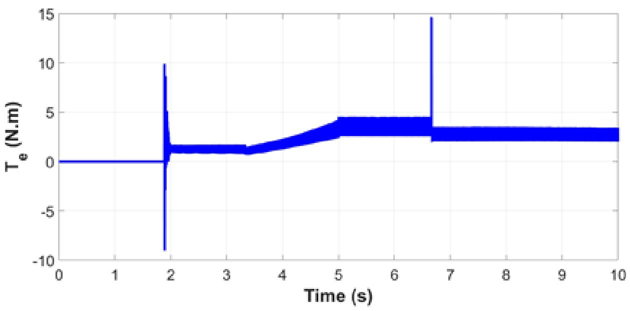

Figure 16. Variation of electromagnetic torque in the unoptimized system

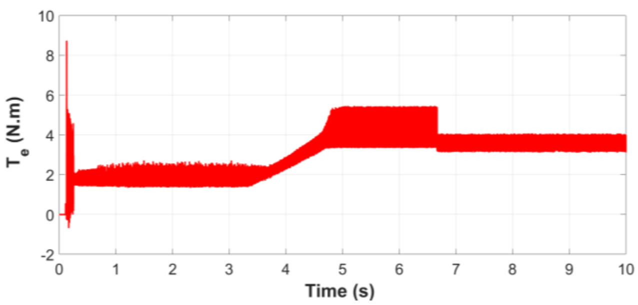

Figure 17. Variation of electromagnetic torque in the optimized system

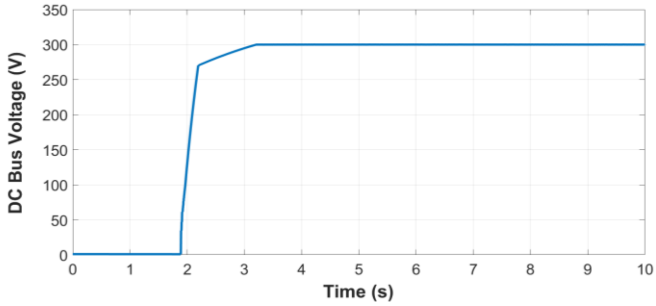

Figure 18. Variation of DC bus voltage in the unoptimized system

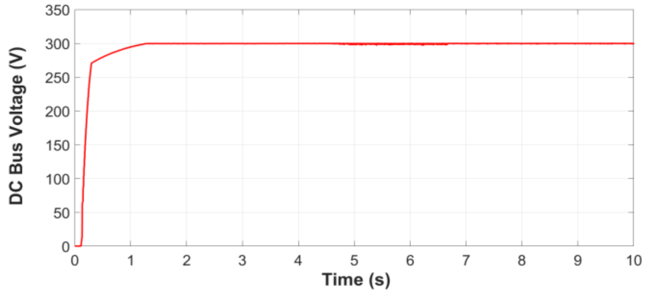

Figure 19. Variation of DC bus voltage in the optimized system

The wind profile, which is given in Fig. 11 is applied to the system input and the simulation is run for 10 s. Then, the variations of the output parameters are examined for the both systems in Fig. 20 and 21, respectively.

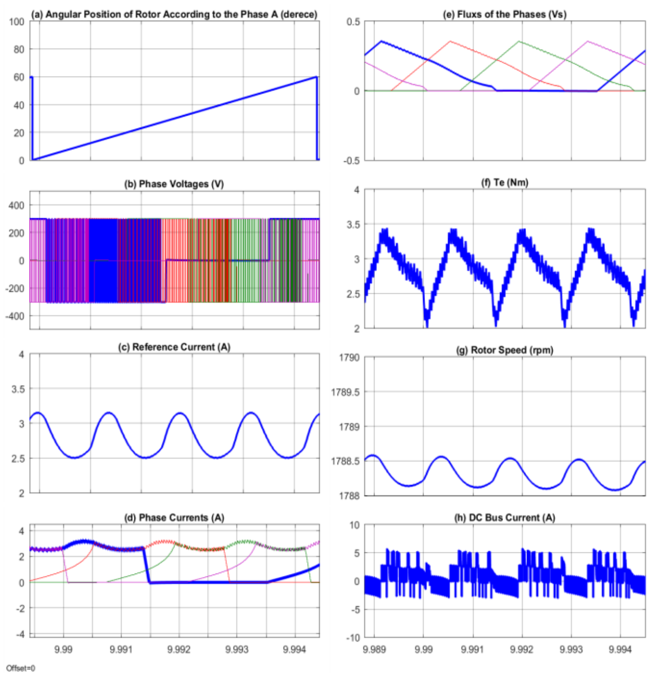

Figure 20. The simulation results obtained from the unoptimized system during a switching period for a wind speed of 12.5 m/s

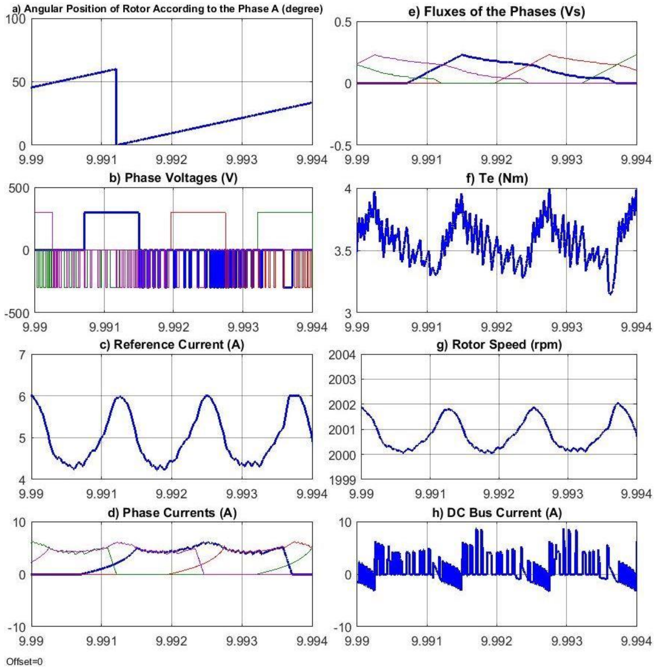

Figure 21. The simulation results obtained from the optimized system during a switching period for a wind speed of 12.5 m/s

As seen from the Fig. 21, the angular position curve of the rotor given in Fig. 21(a) changes from 0° and 60° which correspond to the aligned position (θ_a). Here, 30° corresponds to the unaligned position (θ_{ua}) for the phase A. Blue, red, green and purple colors refer to the phases A, B, C and D in Fig. 21(b), (d) and (e), respectively. The voltage of each phase is shown in Fig. 21(b). For the phase A, the switches S_{A1} and S_{A2} of the phase A in the AHB are opened at θ_{on}. The DC excitation voltage is applied to the phase winding until the actual phase current reaches the reference phase current. Then, both switches are closed and the current flows through the diodes D_{A1} and D_{A2}. In the situation that the value of the phase current is smaller than the reference current, S_{A2} is opened. Thus, the regeneration of the phase current is achieved by using the induced EMF. When the actual phase current equals to the reference value, the switch S_{A2} is closed and the current flows back to the DC generation bus via diodes D_{A1} and D_{A2}. This process is repeated until θ_{off}. The waveform of the reference current is shown in Fig. 21(c). In this curve, some ripples are seen at the phase change points. The actual phase current waveform is illustrated in Fig. 21(d). It is seen that it follows the reference current. However, high frequency fluctuation is occurred because of the hysteresis current control. The flux connections of the phase windings are examined in the Fig. 21(e). The maximum value of the fluxes is 0.3 Vs near the zero aligned position at θ_{on} and then, it also drops to zero when the phase current reduces to zero.
The curve of the SRG electromagnetic moment T_e is obtained in Fig. 21(f). Thanks to the hysteresis current control, a low amplitude high frequency torque ripple is observed. Besides, a torque ripple with larger amplitude and low frequency is obtained at the change of the phases. The rotor speed of the SRG is illustrated in the Fig. 21(g). The torque ripple causes the ripple in the rotor speed. The DC generation bus current is also seen in the Fig. 21(h). Due to the switching angles where two phase currents are produced at the same time, 10 A peaks are seen in the curve of the current. The negative values in the curve mean that the current flows from the excitation bus through the D_E excitation diode. As a result, in this paper, the comparison of the optimized and unoptimized results is realized and the power gain obtained from the optimized system is calculated for different wind speeds in Table 3.

Table 3. The comparison of the optimized and unoptimized results obtained from the designed MATLAB/Simulink model

	Unoptimized System		Optimized System		
Wind Speed (m/s)	Turbine Output Power (W)	SRG Shaft Speed (rpm)	Turbine Output Power (W)	SRG Shaft Speed (rpm)	Power Gain (%)
8.6	178	1250	238	1377	33.70
12.5	550	1840	745	2000	35.45
13.8	760	2060	1005	2210	32.23

As seen from the results in Table 3, in the optimized system, turbine output power and shaft speed values of the SRG are higher than the unoptimized system. While the highest values of them are also obtained in the wind speed of 13.8 m/s, the highest power gain is obtained in the wind speed of 12.5 m/s for the optimized system.

Conclusion

In this paper, a MPPT is carried out using the blade tip speed ratio method for a variable speed wind turbine system whose the rated output power is 745 W with 8/6 poles 4-phase SRG. Besides, an optimization of the SRG is realized by determining the optimum turn-on and turn-off angles where the minimum torque ripple occurs. The results obtained from the optimized model are compared with that of the model without any optimization. According to this comparison, the obtained results are given as follows.

- In the non-optimized operating situation that is constant switching angles for all speed values, the maximum power point in the system cannot be followed for three different wind speeds applied to the input. An excessive speed and torque fluctuations also occur in the system, and the SRG operates with the low efficiency due to not reaching the nominal phase current value. These results show that the AHB converter circuit has great importance about the efficiency of the SRG.
- In the optimized operating situation, different switching angles are set so that minimum torque fluctuation will occur for all speed values. It has been observed that the system works more stable, responds quickly to the changes in the wind speed, and follows the maximum output power point with great accuracy.
- In addition, an average of 33% power gain is achieved by the optimization method at the wind speeds of 8.6 m/s below the nominal wind speed in terms of the output power and 12.5 m/s, which is the nominal wind speed, compared to the unoptimized system. At a wind speed of

13.8 m/s above the nominal wind speed, the turbine output power also decreases due to the drop of the turbine power coefficient which is caused by exceeding the optimum value of the blade tip speed ratio in the optimized system. Thus, a small drop in the power gain is observed.

In conclusion, it is observed from this study that the use of SRGs in variable speed WPP with the right optimization methods is the right choice in terms of obtaining more efficiency from the system due to less losses compared to the conventional generators.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person / institution in the article prepared.

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