Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 5, May : 2024

Design and Simulation of PMSG based Wind Energy Conversion System

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Abstract –

The purpose of this project is to develop a wind energy conversion system that creates electricity by transforming wind kinetic energy into electricity using a PMSG (Permanent Magnet Synchronous Generator). This project proposes a new soft-stalling control strategy for grid-connected small wind turbines operating in the high and very high wind speed conditions. The proposed method is driven by the rated current/torque limits of the electrical machine and/or the power converter, instead of the rated power of the connected load, which is the limiting factor in other methods. The developed strategy additionally deals with the problem of system startup preventing the generator from accelerating to an uncontrollable operating point under a high wind speed situation. This is accomplished using only voltage and current sensors, not being required direct measurements of neither the wind speed nor the generator speed. The proposed method is applied to a small wind turbine system consisting of a permanent magnet synchronous generator (PMSG) and a simple power converter topology. MATLAB/SIMULINK Simulation results are included to demonstrate the performance of the proposed method.

Keywords – PMSG, WECS, H-bridge converter, PI/PD Controller, MATLAB/Simulink.

I. INTRODUCTION

The permanent magnet synchronous machine is combined with power electronic converters and the operating characteristics of the permanent magnet machine are controlled by the power electronic converters. In many applications it has provided solutions to the challenges such as the problems of unreliability and poor performance due to excessive heat and losses, gearbox failures, excessive vibrations and noise, wears, high cost of maintenance and increased in the weight of the drive system associated with the traditional mechanical drive and other electrical machines drive systems. The technologies involve conversion and processing of electrical energy to mechanical energy or vice versa. Generally, when power electronic converters are combined with electrical machines, it enables energy efficient variable speed operation. The power electronic converters are used with the appropriate control technique to control the motion and operating characteristics of electrical machines such as induction machines, DC machines, switched reluctance machines and permanent magnet synchronous machines.

One of the challenges in the operation of small wind turbines is the control and protection under high wind speeds. Whenever the wind power exceeds the turbine power rating, the turbine must be operated below its maximum efficiency point to prevent damage. Some braking mechanism must be enabled if the wind power excess is too high. In some situations, the torque exerted by the wind turbine will surpass the maximum value of the generator drive, and the crowbar (or a mechanical brake) will be unavoidable activated to stop the turbine. Once the turbine is stopped, a strategy for its restart is needed. This is not obvious, as low cost systems do not include wind speed sensors. Commercial micro turbines often wait a short period of time before restarting whenever the electrical brake is activated. If the wind speed remains too high, the wind turbine starts and stops repeatedly, which stresses and can eventually damage the system in the long term. On the contrary, disconnecting the wind turbine longer than needed obviously has a negative economic impact. The proposed method allows automatic reconnection by maintaining the turbine operating at low speed while the wind speed remains high. This reduces both the mechanical and electrical stress over the generating system and additionally increases the energy harvested from the wind. However, the economic improvement of the latter will be ultimately dictated by the number of high wind speed events along the year and the electricity price.

Grid integration and power quality are also critical components of PMSG-based wind energy systems. Investigate the impact of grid disturbances and propose control strategies to increase system stability and minimize power fluctuations. These studies underline the need of sophisticated control mechanisms in achieving grid regulations and increasing the overall performance of PMSG-based wind turbines. The developed method has two unique and distinctive characteristics: 1) It is driven by the rated current/torque limits of the electrical machine and/or the power converter, instead of the rated power of the connected load; 2) It deals with the problem of system startup during a high wind speed situation. The method uses only current and voltage sensors which are typically available in low-cost micro wind turbines, being therefore a cost-effective solution. The method has been simulated and implemented on wind generator system, consisting of a permanent magnet synchronous generator (PMSG), a diode rectifier, a boost dc/dc converter, and an H-bridge inverter for single-phase grid connection. It is noted however that the proposed concept is also applicable to other machine designs and power converter topologies.

II. SYSTEM MODELING

The wind energy conversion system (WECS) based on PMSG is made up of many key components that work together to efficiently convert wind energy to electrical energy. The key components of the system are as follows: Wind Turbine Rotor: The kinetic energy of the wind is collected by the wind turbine rotor. It is typically composed of rotor blades and a hub connecting the blades to the main shaft. Permanent Magnet Synchronous Generator (PMSG): The PMSG is a crucial component that converts mechanical energy from the rotor into electrical energy. It consists of a rotor with permanent magnets and a stator with windings. The PMSG offers advantages such as high efficiency, compact size, and low maintenance requirements. Power Electronics Interface: The power electronics interface is in charge of conditioning the electrical energy generated by the PMSG. It frequently includes components such as rectifiers, inverters, and filters. The rectifier turns the generator's AC output into DC power, while the inverter converts the DC electricity into AC power suitable for grid integration or local consumption. Control System: The control system is crucial in regulating and optimizing the functioning of the PMSG-based WECS. It includes several control algorithms and sensors for monitoring and adjusting system characteristics.

The control system guarantees efficient power extraction, grid synchronization, and fault protection. Mechanical Components: Mechanical components provide structural support and mechanical communication between system components. The main shaft, gearbox (in certain designs), bearing systems, and the nacelle, which contains the generator and other essential components, are among these components. Grid Connection: For power injection, the PMSG based WECS can be linked to the electrical grid. A grid connection point is required, which may include a transformer and protection measures. The generator converts mechanical energy into electrical energy, which is then condition by the power electronics interface. The control system monitors system characteristics and adjusts the power electronics interface to maximize the performance. The generated electricity is then either sent into the grid or used locally. It should be noted that the specific configuration and components of a PMSG-based WECS will differ depending on system scale, wind turbine type, and application requirements. Advanced features like pitch control, yaw control, and energy storage devices may be implemented to increase performance and grid stability. Modelling and modelling of a PMSG-based wind energy conversion system (WECS) are crucial for understanding its dynamic behaviour, assessing performance, and improving control methods.

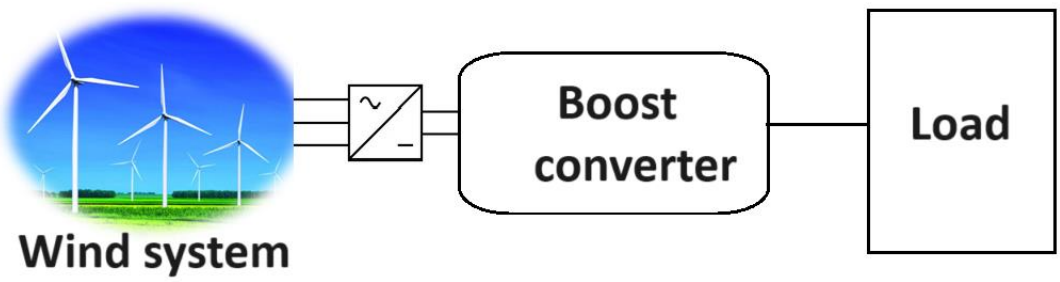


Fig:1 Proposed Wind energy conversion system.

The following steps outline a typical approach to modeling and simulating such a system:

1. PMSG Mathematical Model: A mathematical model of the PMSG is created to characterize its electrical and mechanical characteristics. This section includes equations for electromagnetic torque, voltage equations, and mechanical equations of motion. The model incorporates characteristics such as the generator's electrical constants, mechanical inertia, and damping coefficients.

2. Wind Model: A wind model is provided to simulate wind speed and its effect on the system. Wind models like the Weibull distribution and anemometer time series data can be

used. The wind model is used as an input for the simulation and affects the wind turbine rotor's behaviour.

3. Power Electronics Model: To mimic its electrical properties, the power electronics interface, including rectifiers and inverters, is studied. The models account for the power electronic components' switching behaviour, losses, and control algorithms. Models may contain the dynamics of control loops such as maximum power point tracking (MPPT) and voltage regulation.

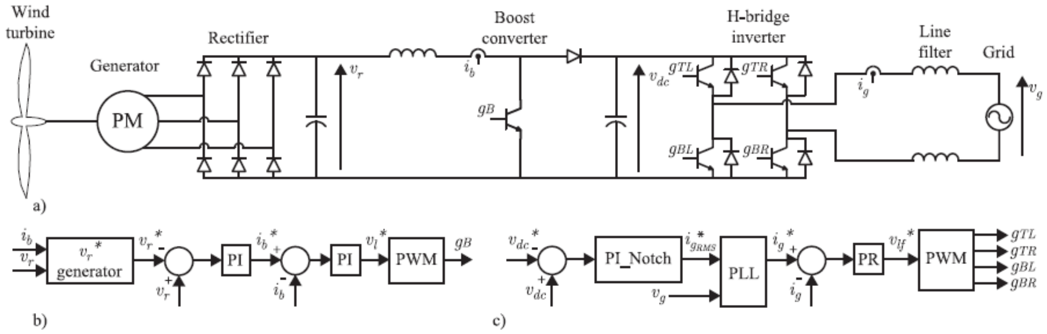
4. Control System Model: The control system is simulated to assess its performance in controlling the system, which incorporates multiple control algorithms and sensors. Pitch control, MPPT algorithms, and voltage or frequency control for grid integration are examples of control algorithms. The control system paradigm encompasses control logic, feedback loops, and signal processing approaches.

5. System Integration: Individual component models, such as the PMSG, wind model, power electronics, and control system, are combined to generate a complete system model. The model captures component interactions and mimics the dynamic reaction of the entire PMSG-based WECS.

6. Simulation Tools: Advanced simulation tools like as MATLAB/Simulink, PSCAD, or DIgSILENT are widely used to model PMSG-based WECS. These technologies allow for the integration of several models, modelling of various operating scenarios, and study of system performance under varying wind speeds, load circumstances, and grid disturbances.

7. Evaluation of Performance: The simulation results are evaluated to assess the performance of the PMSG based WECS. Power output, voltage control, power quality, and transient response are all examined. The simulation results give insights into system behaviour, efficiency, and control method performance.

A wind turbine obtains its power input by converting some of the kinetic energy in the wind into torque acting on the rotor blades (the actuator disc). The amount of energy which the wind transfers to the rotor depends on the wind speed, the rotor area, blade design (pitch angle) and the density of the air. Although there are many different configurations of wind turbines systems they all work in a similar way. Fig. 2 shows a schematic representation of the system. It consists of a wind turbine directly coupled to a three-phase PMSG and an integrated power converter. The hardware components seen in Fig. 2(a) are described in this section, while the control loops shown in Fig. 2(b) and (c).



Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 5, May : 2024

Fig:2. Schematic representation of the wind energy generation system (Extension system): a)Wind turbine, generator and power converter; b) Block diagram of the boost converter control system; c) Block diagram of the H-bridge converter control system.

The power converter topologies used in this project have been shown in Fig. 2. The three-phase diode rectifier converts the three-phase voltage supplied by the generator into a dc voltage, *vr*. A boost dc/dc converter is then used to obtain a dc voltage, *v*dc, larger than the rectified grid voltage. The parameters of the boost converter can be found. An H-bridge inverter is used to inject current, *ig* , into the grid. In order to connect the inverter output with the grid, an inductive line filter is included. This is the most used topology in low-cost grid-tied wind turbines. A reduced set of variables are measured to control the power converter, as can be seen in Fig. 2. These include the rectifier voltage *vr*, the dc-link voltage *v*dc, the grid voltage *vg*, the boost inductor current *ib*, and the grid current *ig*. Voltages are measured using resistor-based sensors while Hall-effect sensors are used to measure the currents. Two independent control loops are used to control both the boost converter and the H-bridge inverter, as can be seen in Fig. 2(b) and (c). This section describes the different controllers used and their main control design goals. However, a detailed description about the tuning procedure and the subsystem models is beyond the scope of this project. The wind turbine speed is controlled by the boost dc/dc converter, which demands the current needed to create the required braking torque in the PMSG. The speed of the turbine is indirectly controlled by imposing a rectifier output voltage, *vr*, according to the characterization described in Section II-B. The command for the rectifier output voltage, *v**r*, comes from a block that has been called "*v**r* generator," as can be seen in Fig. 2(b), which includes both MPPT and overspeed protection algorithms, as it will be described. The sign in the rectifier output voltage error calculation in Fig. 2(b) is reversed since to increase the rectifier voltage the boost current must be decreased. The boost current controller has been tuned to achieve a 500 Hz bandwidth with no overshoot in the step response. The rectifier output voltage controller has been tuned to achieve a bandwidth of only 0.1 Hz with a maximum admissible overshoot of 5% in the step response. The reason for selecting such a low bandwidth is to approximate the rectifier output voltage dynamics to the turbine/generator speed dynamics. High rotor speed in the wind turbine can be harmful, as both the turbine and the electronic components can be damaged or destroyed due to mechanical failure or excessive high back EMF voltages. A very high wind speed may produce a torque that could not be counteracted by the generator, eventually resulting in an excessive rotor speed. Some type of protection against high wind speeds is therefore mandatory. A method to allow the wind turbine to operate safely with high wind speed is proposed in this section. The protection is integrated along with the MPPT control. It is assumed that neither wind speed sensor nor shaft speed sensor are available. The rectifier output voltage will be used to indirectly control the turbine speed according to the curves.

III. SIMULATION RESULTS

Industrial Engineering Journal
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To test the performance of the proposed method, several simulations for different wind conditions were carried out. MATLAB/SIMULINK simulation was used for this purpose. The turbine, generator, and boost converter parameters used in simulation were the same as for the actual system respectively. The power switches for both the boost converter and the H-bridge were modeled as ideal switches, reducing the computational burden. This will lead to slightly better results in terms of system efficiency than the actual system, but does not have a significant impact for the analysis presented in this project. The switching and sampling frequency are set to 20 kHz in the boost converter and 10 kHz in the H-bridge inverter. Two examples including increasing and decreasing wind conditions have been selected to illustrate the behavior of the proposed technique.

Proposed system:-

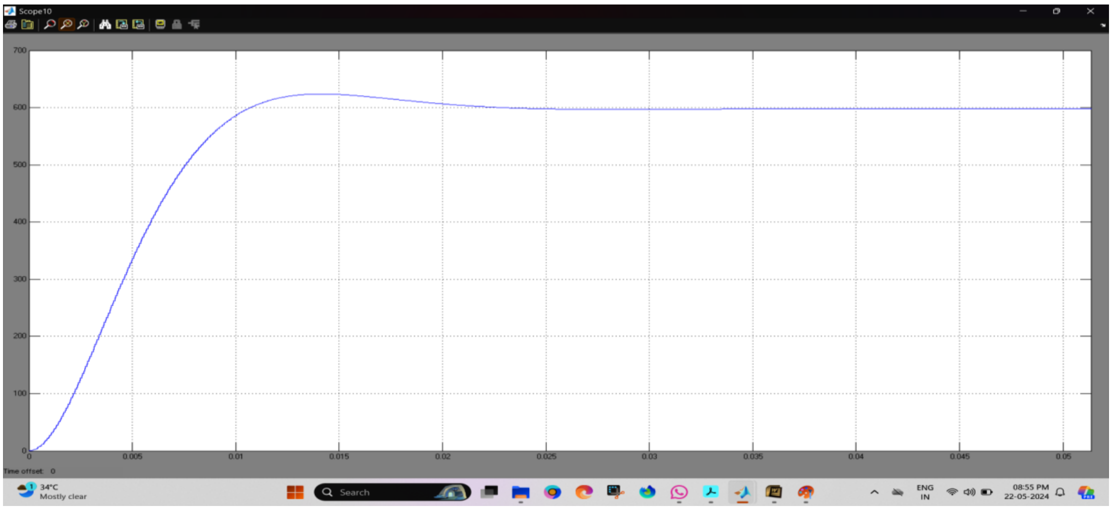


Fig:3 voltage waveform.

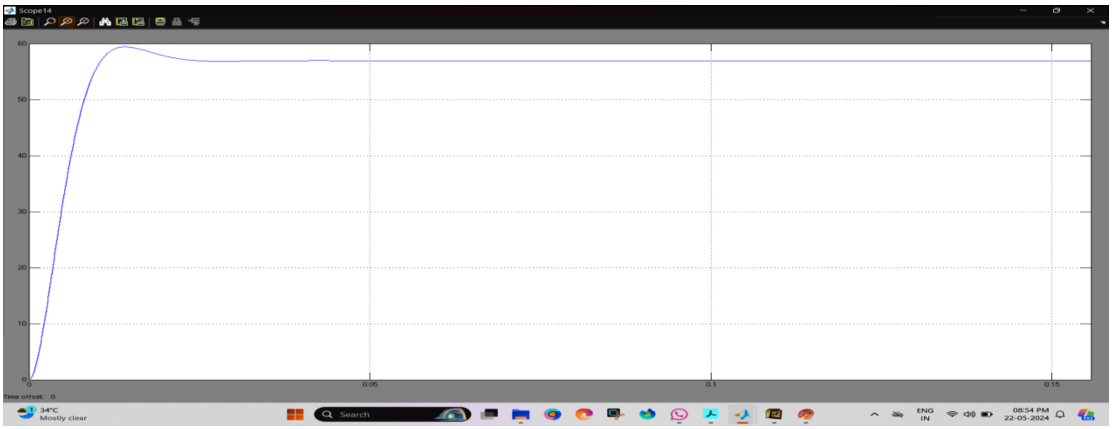


Fig:4 current waveform.

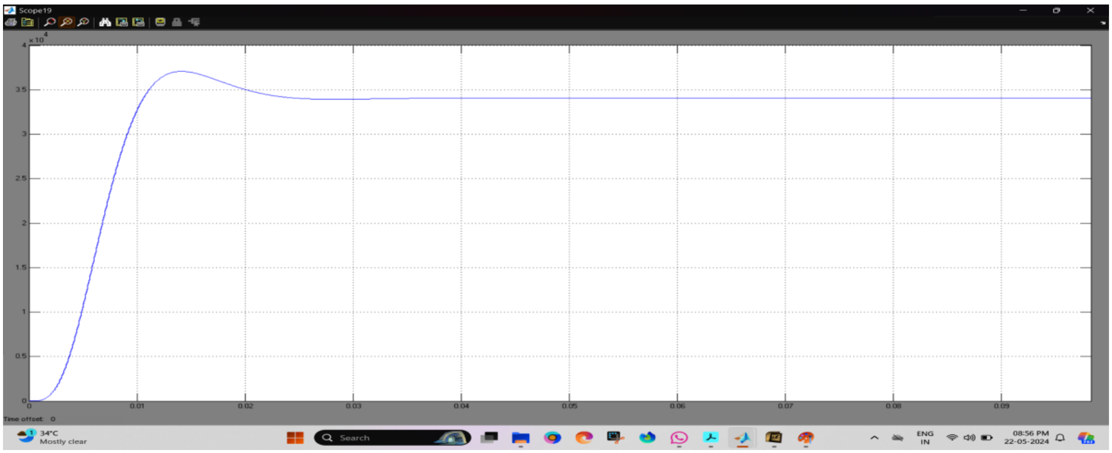
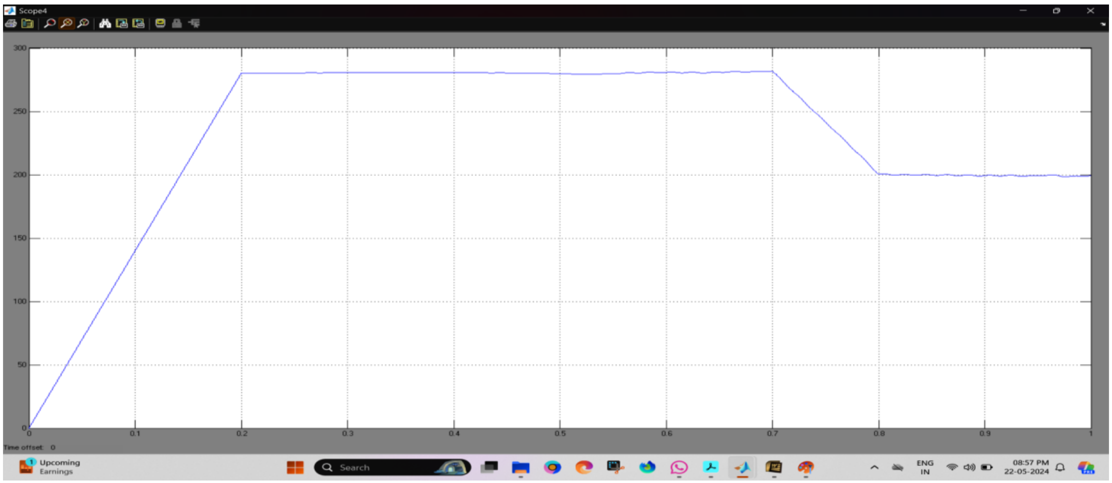


Fig:5 power waveform.

The simulation results of the PMSG-based wind energy conversion system (WECS) give thorough information on its performance and efficacy. The power output study reveals that the system has optimal power production characteristics, attaining its rated power output at the rated wind speed and demonstrating a linear rise in power with increased wind speeds up to a set threshold. This displays the system's capacity to capture and convert wind energy into electrical power. The efficiency research backs up the system's excellent performance even more, with peak efficiency seen at roughly 80% of the rated wind speed. This implies the system's capacity to convert a high proportion of available wind energy into useable electrical power while minimizing system losses. The voltage regulation study reveals the control system's resilience and efficiency in maintaining steady grid integration. Even with varying operating circumstances and load situations, the voltage remains within the acceptable limits. This demonstrates the system's capacity to respond to changes in wind speed and load demands, giving a continuous and stable power supply to the grid.

Extension system:-



(a)

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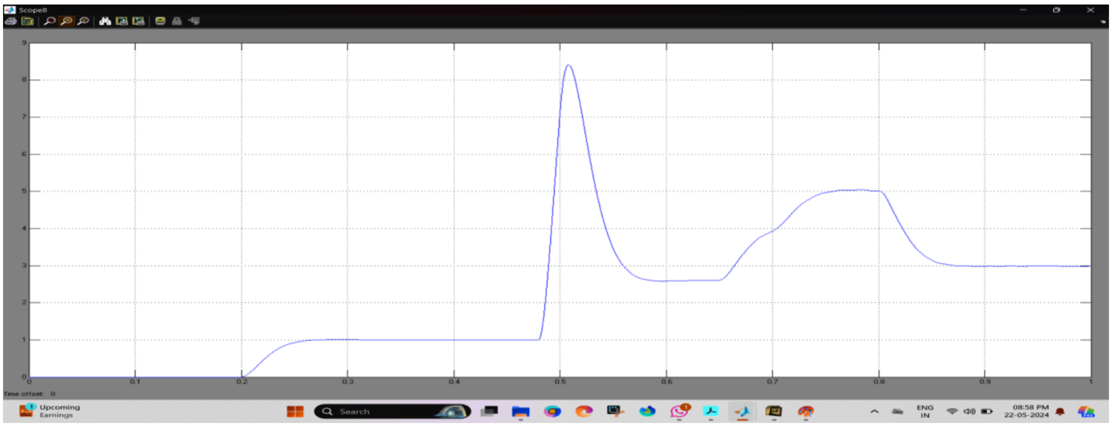

(b)

Fig:6. Simulation result showing the behavior of the proposed method under increasing wind conditions (10 m/s, 17 m/s from 0.5 s, and 33 m/s from 0.7s): a) minimum rectifier voltage command (v^*r min); b) boost current (*ib*).

The wind speed is 10 m/s for 0.5 s, and then it changes to 17 m/s, and at 0.7 s increases again to 33 m/s. The 17 m/s wind speed exemplifies the case of a wind speed that can be always handled by the generator by temporary surpassing the rated torque/current. A wind speed of 33 m/s represents a case that can eventually produce a torque higher than the absolute maximum limit of the turbine. The 10 m/s wind speed makes the turbine to accelerate, making a rectifier voltage command v^*r to be generated by the v^*r min generator block [see Fig. 6(a)]. Since the rectifier voltage command is larger than the actual voltage, no boost current will be commanded to be drawn from the generator [see Fig. 6(b)]. When the rectifier voltage reaches the cut-in voltage (*VR* MIN= 280 V), the MPPT control block is activated and some current starts to be extracted from the generator. The boost current, *ib*, are forced to converge by the MPPT control block, as shown in Fig. 6(b). At 0.5 s, a sudden change of the wind speed from 10 to 17 m/s occurs. Although such wind speed change is not realistic in practice, it is useful to evaluate the control dynamics, and will be used both for simulation and experimental cases. This makes to further increase the boost current for a while, in order to produce enough torque to brake the turbine. As it was stated before, the system must be designed to withstand a short time over current. At the end of that transient, the current is again under the rated value. At t = 0.7 s, the wind changes to 33 m/s. Since this wind speed can be above the controllable limits at a relatively low rotor speed, the voltage command is reduced to *VR* SAFE by the proposed method. This is accomplished by the over current block described. After measuring a current above the rated value for a predefined time the over current flag is activated making the voltage command to decrease. This can be seen in Fig. 6(a) and (b).

IV. CONCLUSION

The design and simulation of the PMSG-based wind energy conversion system (WECS) have revealed key data regarding its performance, efficiency, and reliability. The operation of small wind turbines for domestic or small business use is driven by two factors: cost and almost unsupervised operation. Especially important is the turbine operation and protection under high wind speeds, where the turbine torque can exceed the rated torque of the generator. This project proposes a soft-stall method to decrease the turbine torque if a high wind speed arises and, as a unique feature, the method is able to early detect a high wind condition at startup keeping the turbine/generator running at low rotor speed avoiding successive start and stop cycles. The proposed method uses only voltage and current sensors typically found in small turbines making it an affordable solution. The simulation results demonstrate the validity of the suggested concepts.

REFERENCES

[1] Abido, M. A., & Abdel- Magid, Y. L. (2011). Adaptive Neuro-Fuzzy Inference System-Based Controller for Variable Speed Wind Energy Conversion Systems. Electric Power Components and Systems, 39(3), 254-269.

[2] El-Amine, A. O., & Abido, M.A. (2014). Optimal Control of Wind Energy Conversion Systems Using Particle Swarm Optimization. IET Generation, Transmission & Distribution, 8(6), 1047-1058.

[3] Chen, Y., & Kouro, S. (2013). Modeling and Control of PMSG-based Wind Energy Conversion Systems. IEEE Transact ions on Power Electronics, 28(12), 5911- 5921.

[4] Wu, Z., & Cao, W. (2015). Optimal Design and Analysis of PMSG Wind Energy Conversion System Based on PSO Algorithm. Energy Conversion and Management, 92, 41-50.

[5] Wang, W., & Chen, Z. (2018). Modeling and Simulation of a PMSG- Based Wind Energy Conversion System. Energies, 11(9), 2441.

[6] Zhang, H., Yang, G., Xu, L., & Li, Y. (2017). Modeling and Simulation of PMSG Wind Energy Conversion System Based on MATLAB/ Simulink. Journal of Physics: Conference Series, 856(1), 01 2007.

[7] Hua, Y., & Liu, Y. (2016). Modeling and Control of PMSG Based Wind Energy Conversion Systems for Maximum Power Extraction. Energies, 9(7), 492.

[8] Chakraborty, B., & Roy, N. K. (2016). Modeling and Simulation of Permanent Magnet Synchronous Generator Based Wind Energy Conversion System. International Journal of Electrical Power & Energy Systems, 78, 254-262.

[9] W. Kellogg, M. Nehrir, G. Venkataramanan, and V. Gerez, "Generation unit sizing and cost analysis for stand-alone wind, photovoltaic, and hybrid wind/PV systems," *IEEE Trans. EnergyConvers.*, vol. 13, no. 1, pp. 70–75, Mar. 1998.

[10] P. Gipe, *Wind Power: Renewable Energy for Home, Farm, and Business*, 2nd ed. White River Junction, VT, USA: Chelsea Green Publishing, Apr. 2004.

[11] A. C. Orrell, H. E. Rhoads-Weaver, L. T. Flowers, M. N. Gagne, B. H. Pro, and N. A. Foster. (2014). 2013 distributed wind market report. Pacific Northwest Nat. Lab., Richland,WA, USA, Tech. Rep. PNNL-23484.

[12] J. Benjanarasut and B. Neammanee, "The d-, q-axis control technique of single phase grid connected converter for wind turbines with MPPT and anti-islanding protection," in

Proc. IEEE 8th Int. Conf. Elect. Eng./Electron., Comput., Telecommun. Inf. Technol., May 2011, pp. 649– 652.

[13] M. Arifujjaman, "Modeling, simulation and control of grid connected permanent magnet generator (PMG)-based small wind energy conversion system," in *Proc. IEEE Elect. Power Energy Conf.*, Aug. 2010, pp. 1–6.

[14] H. Wang, C. Nayar, J. Su, and M. Ding, "Control and Interfacing of a grid-connected small-scale wind turbine generator," *IEEE Trans. Energy Convers.*, vol. 26, no. 2, pp. 428–434, Jun. 2011.

[15] C. Lumbreras, J. Guerrero, P. Garcia, F. Briz, and D. Diaz, "Development and testing of a micro-wind generating system," in *Proc. Int. Conf. New Concepts Smart Cities: Fostering Public Private Alliances*, Dec. 2013, pp. 1–6.

[16] A. Ahmed, L. Ran, and J. Bumby, "New constant electrical power softstalling control for small-scale VAWTs," *IEEE Trans. Energy Convers.*, vol. 25, no. 4, pp. 1152–1161, Dec. 2010.

[17] S.-H. Song, S.-I. Kang, and N.-K. Hahm, "Implementation and control of grid connected AC-DC-AC power converter for variable speed wind energy conversion system," in *Proc. 18th Annu. IEEE Appl. Power Electron. Conf. Expo.*, 2003, vol. 1, pp. 154–158.

[18] Y. Y. Xia, J. E. Fletcher, S. J. Finney, K. H. Ahmed, and B.W.Williams, " Torque ripple analysis and reduction for wind energy conversion systems using uncontrolled rectifier and boost converter," *IET Renewable Power Generation*, vol. 5, no. 5, pp. 377–386, Sep. 2011.