# MODELING AND CONTROL OF SMALL WIND TURBINE IN THE HIGH WIND SPEED REGION

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***Abstract*- 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. The project also shows the limitations of using the stator back electromotive force to estimate the rotor speed in PMSG connected to a rectifier, due to significant *d*-axis current at high load.**

## I. INTRODUCTION

In the past several years, wind energy has been one of the fastest growing energy sources in the world. In the last two decades there have been many technological advances in the wind power industry, making this source of energy more reliable and profitable. In present days, wind power generation can be commercialized and penetration into the present power systems is increasing. In addition, wind power generation has been gaining acceptance from investors and more wind farms are being built because this industry has become profitable. The cost of energy from wind has dropped to the point in which there are places that the price of wind energy is competitive with conventional sources of energy, even without incentives. Wind energy not only has economical impact on our society, but it has a big environmental and social impact as well. The use of wind energy reduces the combustions of fossil fuels and the consequent emissions. It also reduces the United States‟ dependence on foreign oil. On the other hand, it creates manufacturing, operation and maintenance jobs and construction jobs. Modern wind turbine technology has been accomplished with the help of many areas, such as material science, computer science, aerodynamics, analytical methods, testing, and power electronics. Without the help of these areas the rapid development of new technologies would not be possible. A relatively new area for wind turbines is power electronics.

Power electronic systems allow synchronization between the wind turbine system and the utility grid and operate the wind turbine at variable speeds, increasing the energy production of the system. In addition, power electronics provide a means to transfer energy to and from storage units, which can allow the storage of excess energy generation for later use. Wind turbine technology has improved significantly in the past 20 years. Modern turbines are more reliable, efficient, cost-effective, and the sound of the turbines has been reduced significantly compared to their predecessors. Although many improvements have been made, there needs to be more work done towards improving wind energy grid penetration, reducing the manufacturing and installation cost, and improving turbine efficiency at all wind speeds. The development of new control strategies to maximize power extraction from the wind and increase turbine efficiency will make wind power generation a more reliable source of energy in the future.

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 microturbines 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. 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 microwind turbines, being therefore a cost-effective solution. The method has been simulated and implemented on a 2.5-kW 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

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. 1 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. 1(a) are described in this section, while the control loops shown in Fig. 1(b) and (c).

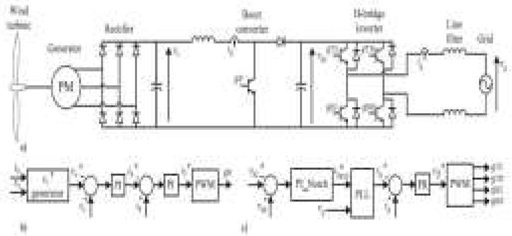


Fig:1. Schematic representation of the wind energy generation system: a)Wind turbine, generator and power converter; b) Block diagram of the boost converter control system; c) Block diagram of the H-bridge converter control system.

A fixed-pitch wind turbine has been used in the present study. The power extracted by a wind turbine depends on the wind speed, the constructive parameters of the turbine, and the rotor speed. However, the power coefficient depends only on the TSR in fixed-pitch turbines. This power coefficient can be approximated by a nonlinear function whose parameters can be estimated from experimental data. Steady-state power versus rotor speed experimental data provided by the turbine manufacturer, including wind speeds up to 26 m/s, have been used in the present study to obtain the power coefficient curve seen in Fig. 2, where *cp* max is the maximum power coefficient obtained with the optimal TSR $\lambda$max. The curve seen in Fig. 2 has been used both in simulations and in the wind turbine emulator to obtain the power and torque exerted by the turbine at different wind speeds, including high wind speeds. The model presents the following limitations:
1) The effect of passive stall over the turbine blades at high wind speed is not considered. This provides a worst-case scenario to the present study from the point of view of high wind speed protection, since the actual torque at high wind speeds would be smaller than the predicted by the model.
2) Dynamic stall effects are not included in the model. Therefore, the torque variations due to excursions from the static power coefficient when the wind speed changes can be seen as disturbances for the proposed control system.
3) Considerations about the possible mechanical stresses, vibrations, and system mechanical or structural failure are not covered in this paper. The study is focused in the protection of the electrical subsystem.

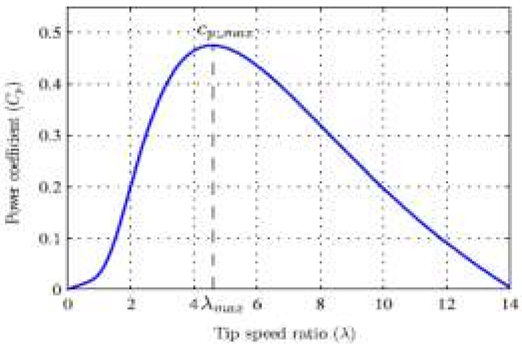
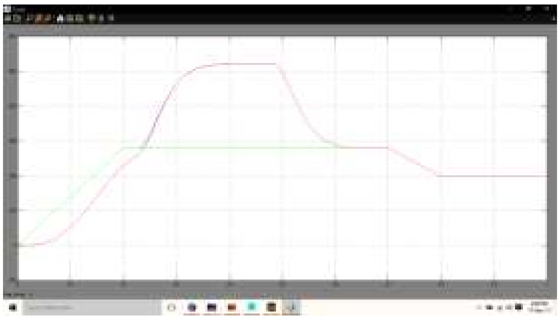


Fig. 2. Power coefficient of the wind turbine as a function of the TSR.

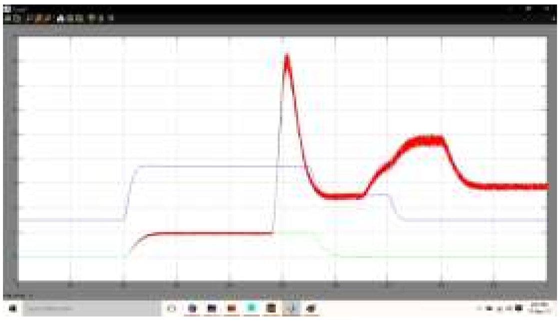
## III. SIMULATION RESULTS

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 paper. 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.

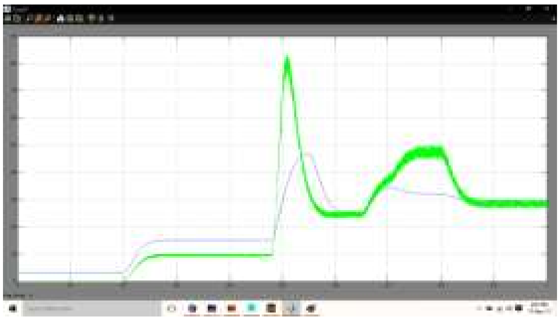
### CASE-A: Increasing Wind Conditions



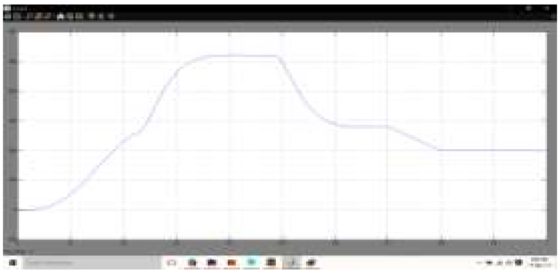
(a) rectifier voltage command ($v_r^*$), rectifier voltage ($v_r$) and minimum rectifier voltage command ($v^*_{r\,\min}$)



(b) boost current ($i_b$), filtered boost current ($\tilde{i}_b$), current limit ($i_{limit}$) and MPPT current target ($i_{mppt}$)



(c) turbine torque ($T_t$) and generator torque ($T_g$)

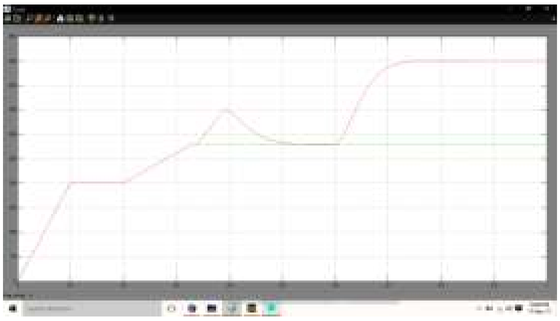


(d) mechanical rotor speed ($\omega_{rm}$)

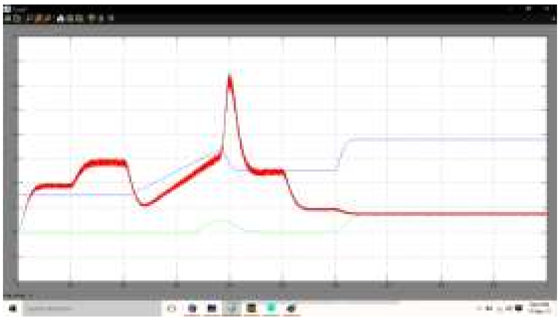
Fig:3. Simulation result showing the behavior of the proposed method under increasing wind conditions (10 m/s, 17 m/s from 0.5 s, and 33 m/s from 0.7s).

Fig. 3 shows an example of the turbine behavior under increasing wind conditions starting from rest. 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. 3(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. 3(b)] and the turbine will speed up at a rate only dictated by the turbine torque [see Fig. 3(c) and (d)]. 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, $ib$ , and the target MPPT current, $i$mppt, are forced to converge by the MPPT control block, as shown in Fig. 3(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. The new wind speed results in a large increase of the turbine torque that must be counteracted by the generator [see Fig. 3(c)]. The required boost current is consequently larger than the rated current and the over speed control makes the voltage command to decrease to $VR$ MIN to reduce the speed, and thus, the turbine torque [see Fig. 3(c) and (d)]. 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. 3(a) and (b).

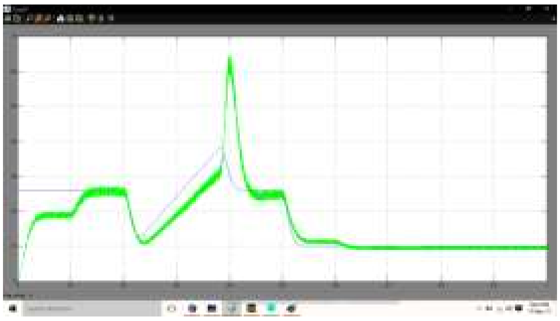
### CASE-B: Decreasing Wind Conditions



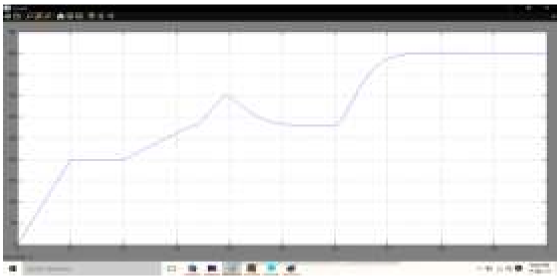
(a) rectifier voltage command ($v^*\ r$ ), rectifier voltage ($vr$ ) and minimum rectifier voltage command ($v^*\ r$ min ).



(b) boost current ($ib$ ), filtered boost current ($\tilde{ib}$ ), current limit ($i$lim it ), and MPPT current target ($i$mppt)



(c) turbine torque ($Tt$ ) and generator torque ($Tg$ )



(d) mechanical rotor speed ($\omega$rm )

Fig:4. Simulation result showing the behavior of the proposed method under decreasing wind conditions (30 m/s, 21 m/s from 0.5 s, and 8.5 m/s from 0.7s).

An example of the turbine behavior under decreasing wind conditions starting from rest can be seen in Fig. 4. The wind speed is 30 m/s for 0.5 s, then it changes to 21 m/s, and at 0.7 s decreases to 8.5 m/s. In this case, the 30 and 21 m/s speeds have been chosen as examples of a wind speed that can exceed the generator maximum capabilities, and a wind speed that can be always handled by transitory surpassing the rated torque, respectively. The $v*r$ min generator block detects an increasing voltage from startup and commands a voltage reference that limits the acceleration of the wind turbine, as can be seen in Fig. 4(a) and (b). Since a current larger than $i$limit is required to produce the necessary torque [see Fig. 4(c)], the voltage command is held equal to $VR$ SAFE once this value is reached. This operating point will prevent the system from repeated start and hard stop cycles, and will keep the generator producing some power at high wind speed. At $t$ =0.5 s, the wind speed decreases to 21 m/s and the voltage command increases to reach the cut-in voltage (280 V) in which the MPPT mode starts. At that point, the voltage command increases in an attempt to make the boost current, $ib$, to match with the $i$mppt command. Since that wind speed can produce torque levels higher than rated torque at some rotor speed in the MPPT range, the system must limit the over current situation. That event is early detected by the proposed method when the actual current surpasses $i$limit , as can be seen in Fig. 4(b). Then the voltage is decreased to $VR$ MIN by transiently surpassing the rated current/torque [see Fig. 4(b) and (c)]. The advantage of the proposed method is that the duration and magnitude of this current transient will be smaller than in case of waiting for the current to surpass the rated value. The wind speed changes to 8.5 m/s at $t$ = 0.7 s. The boost current drops since a lower torque is required to maintain the turbine speed/rectifier voltage. Therefore, after some predefined time the over current flag is set to zero and the MPPT control is reactivated. A higher rectifier voltage is then commanded to force to boost current $ib$ to follow the MPPT current command, $i$mppt, as can be seen in Fig. 4(a) and (b). The simulations show that the method works as intended.

## IV. CONCLUSION

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 proposed concepts. This project also shows that commonly used machine and rectifier models assuming unity power factor do not provide accurate estimations of the generator speed in loaded conditions, even if the resistive and inductive voltage drop are decoupled, due to the significant circulation of $d$-axis current if a PMSG is used. This project proposes using a precommissioned LUT whose inputs are both the rectifier output voltage and the boost current.

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