

Smoothing the Power Output of a Wind Turbine Group with a Compensation Strategy of Power Variation

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Abstract-This paper proposes a new scheme to reduce the output power variation range of a wind turbine group without an energy storage system. This proposal is based on the active power compensation principle for each wind turbine. In this research, the wind turbine operates in the active power control mode. The reference active power is calculated in such a way that it compensates for the difference between the average output power and the actual output power. To verify and evaluate the proposed method, we simulated a group of two 1.5MW-wind turbines in the Simulink environment of MATLAB. Simulation results were compared to the ones of a wind turbine group without any smoothing scheme and the ones of the same group with the Exponential Moving Average method. From this comparison, we can conclude that with the proposed method, the actual output power of the wind turbine group becomes smoother than that of the wind turbine group without any smoothing scheme. Moreover, the performance of the wind turbine group with the proposed method is better than that of the wind turbine group with the Exponential Moving Average method.

Keywords-DFIG; fluctuating compensation; power control; smoothing power; wind turbine

I. INTRODUCTION

The energy demand has been increased rapidly in many developing countries whereas conventional energy resources are gradually exhausted [1]. This has boosted the exploiting of renewable energy resources such as wind, solar, geothermal, etc. to gradually replace fossil fuel-based resources like coal, oil, and natural gas. In many countries, wind energy has been practically accounted for a substantial rate in electricity demand [1]. However, the main drawback of wind turbines or wind farms is that they bring a negative impact on the connected grid because the output power fluctuates due to the natural variation of wind speed [2]. Until now, many useful schemes were proposed to reduce the fluctuation in the output power of a wind turbine [2-19]. These schemes can be generally divided into two groups, energy storage system utilization [2-3, 8-13] and storage energy system misutilization [2,4-7]. By using an energy storage system as battery, super capacitor, etc. [8-13], we can adjust the amount of active power charging/discharging from the energy storage system to smooth the output power quite easily and hence, wind turbines can

completely operate on their optimal power points to yield maximum available power. However, to obtain this benefit we must invest on the storage energy system installation and expect expensive operation cost. In contrast with the method of the energy storage system utilization, the controller utilization is hard to make the wind turbine operate completely on the maximum-power-point-tracking curve [2, 4]. Moreover, by using the controller, the output power of the wind turbine is hardly as smooth as that using the energy storage system. The main reason is that it cannot store the redundant electrical power to release it as the output power is inadequate. However, the misutilization of an energy storage system does not require huge investments and maintenance cost.

For the controller utilization of the wind turbine, some methods to smooth the power output of a wind turbine are inertia control [7], pitch control [14-17], DC link voltage control [18], etc. Utilizing the inertia of the wind turbine can cause stress on its mechanical system whereas it is hard to respond quickly by using the pitch controller and a large amount of wind energy is wasted. In both pitch control and inertia methods, an anemometer must be used to provide the wind speed variation to the controller [2]. The DC voltage control method works on the principal of utilizing the DC link of the power converter, which is interfaced to the connected grid, as a small storage energy system to charge/discharge a small electrical energy amount during its operation interval, and hence the voltage on the DC-link is varied and this may bring a negative impact on the voltage at the point of common connection. Moreover, this method is only applied in wind turbines that use a full-scale converter and is hard to implement in a Doubly Fed Induction Generator (DFIG) wind turbine because of the converter's small capacity. Another way to smooth the output power is the use of the Exponential Moving Average (EMA) method to determine the average reference signal for the controller. Depending on the smooth factor, this method can be either effective or ineffective. It is also noted that this method was not only used in the controller of a wind turbine but also in the controller of the energy storage system [4, 13, 19].

The objective of this research is the proposition of a new scheme for smoothing the output power of a wind turbine

group without an energy storage system. The basis of the proposed scheme is to compensate the active power for the fluctuation in the output power. To obtain this objective, one must calculate the reference power, using it as an input signal of the RSC controller, such that it can compensate the variation in the actual output power. This scheme is evaluated via simulations in the Simulink environment of MATLAB software. The simulation results of a wind turbine group with the proposed method will be compared to the ones without a smoothing method and with the EMA method.

It is noted that in order to evaluate the performance of the methods that smooth the output active power, we will use two indices, namely the smoothing function ΔP_{smooth} and the electrical energy output of wind turbine group as (1)-(2) [3]:

$$\Delta P_{smooth} = \int \left| \frac{d}{dt} P_o \right| dt \quad (1)$$

$$E = \int P_o dt \quad (2)$$

It is desired that the smoothing function ΔP_{smooth} should be smaller in order for the output power to become smoother. Moreover, the wind turbine group is always expected to withdraw as much electrical energy as possible and hence, a preferable method will provide a small value of the smoothing function and a high value of output electrical energy.

II. RESEARCH CONFIGURATION

In this research, we consider a wind turbine group, as shown in Figure 1, in which a DFIG with 1.5MW capacity is employed.

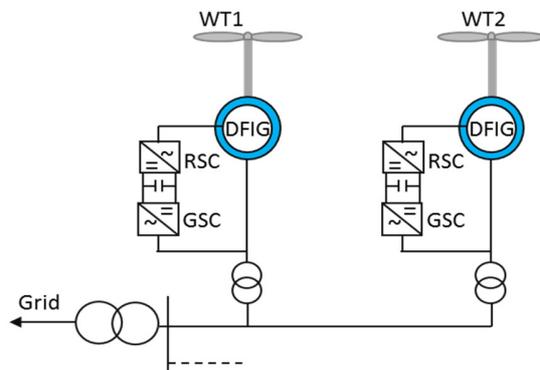


Fig. 1. Configuration of the wind turbine group.

Generally, a DFIG wind turbine system consists of a 3-blade system, a shaft system, and a DFIG [20]. In the DFIG wind turbine, the stator winding is connected directly to the grid whereas the rotor winding is interfaced to the grid via a back-to-back small capacity converter [21, 22]. This converter consists of a Rotor Side Converter (RSC), a Grid Side Converter (GSC) and a DC-link. Via the RSC controller, we can adjust the output active power of the wind turbine.

A. Wind Turbine

The blade system converts wind energy to mechanical energy on its shaft. The efficiency of the conversion is

represented by $C_p(\lambda, \beta)$, namely power coefficient [8, 23]. This coefficient is reliant on both pitch angle β and tip speed ratio λ [8, 24]:

$$\lambda = R \frac{\omega_r}{V_w} \quad (3)$$

where R is the length of the blade, ω_r is the rotational velocity of the shaft, and V_w the wind velocity at the wind turbine location.

According to [8, 23], the coefficient $C_p(\lambda, \beta)$ versus the tip speed ratio λ at different values of β of a typical wind turbine is shown in Figure 2(a) [8, 26]. It is easy to see that with a constant pitch angle, the power coefficient $C_p(\lambda)$ reaches a maximum value at an optimal tip speed ratio. When we keep $\beta=0$, $C_p(\lambda)$ will reach its maximum value C_{pmax} at λ_{opt} [25]. At a wind velocity V_w and rotational velocity of shaft ω_r , the mechanical power on the wind turbine shaft is defined by [8, 24]:

$$P_m = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) V_w^3 \quad (4)$$

where ρ is the density of air at the wind turbine location.

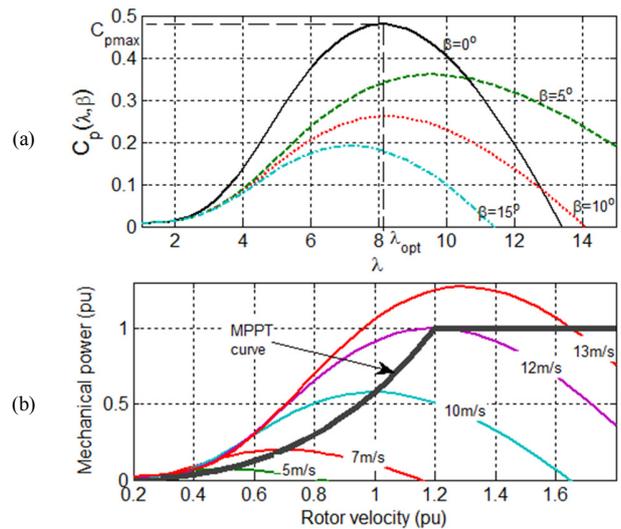


Fig. 2. (a) Power coefficient versus tip speed ratio at different pitch angles and (b) mechanical power versus rotor velocity at different wind velocities.

Obviously, this mechanical power is reliant on the cubic of the wind velocity V_w . When the wind velocity is over the rated value, the wind turbine should be remained at its rated power by adjusting the pitch angle β . By contrast, when the wind velocity is below the rated value, the pitch angle should be kept at a minimum value and the rotor speed should be adjusted so that the wind turbine operates at its optimal point $(\lambda_{opt}, C_{pmax})$. From (3), (4), for $C_p = C_{pmax}$ and $\lambda = \lambda_{opt}$, we obtain [24]:

$$P_m = \frac{1}{2} \rho \pi R^2 C_{pmax} V_w^3 = K_{opt} \omega_{r_{opt}}^3 \quad (5)$$

where:

$$K_{opt} = \frac{1}{2} \rho \pi R^5 C_{pmax} / \lambda_{opt}^3 \quad (6)$$

$$\omega_{r_{opt}} = \frac{\lambda_{opt} V_w}{R} \quad (7)$$

When the wind velocity varies, the optimal rotor velocity $\omega_{r_{opt}}$ will be varied proportionally (7). Hence, the locus of optimal operation point which is named Maximum Power Point Tracking (MPPT) curve is computed as in (8). This locus is represented in Figure 2(b).

$$P_{mppt} = \frac{1}{2} \rho \pi R^2 C_{pmax} V_w^3 = K_{opt} \omega_r^3 \quad (8)$$

B. Doubly Fed Induction Generator

A DFIG is principally an asynchronous generator and it consists of 2 windings, namely a stator winding and a rotor winding. In the dq axis system, the rotor side voltage of a DFIG is described as [24]:

$$v_{rdq} = R_r i_{rdq} + \sigma L_m \frac{di_{rdq}}{dt} + \omega_s \sigma L_m \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} i_{rdq} + \frac{s L_m}{L_s} \begin{bmatrix} 0 \\ V_s \end{bmatrix} \quad (9)$$

where:

$$\sigma = \frac{L_r}{L_m} - \frac{L_m}{L_s} \quad (10)$$

$$s = 1 - \frac{\omega_r}{\omega_s} \quad (11)$$

R_r is the resistance of rotor winding, L_r, L_s , and L_m represent the inductance of the rotor winding, the stator winding, and the magnetizing core respectively, v_{rdq} and i_{rdq} are the rotor voltage and rotor current in the dq axis system, ω_s is the flux rotational velocity or angular frequency in the stator winding, s is the slip factor, and V_s the voltage magnitude in the stator winding terminal.

The active power output of the DFIG in total is calculated as [24, 25]:

$$P_e = P_s + P_r = (1 - s)P_s \quad (12)$$

where P_r is the active power exchanging to grid via the rotor side and P_s the active power supplying to the connected grid via the stator side and in the dq axis system. It is defined as [24]:

$$P_s = \frac{2}{3} V_s i_{sq} = -\frac{2}{3} \frac{L_m}{L_s} V_s i_{rq} \quad (13)$$

In the dq axis system, the electromechanical torque of the DFIG can be calculated as:

$$T_e = -\frac{2}{3} \frac{L_m}{L_s \omega_s} V_s i_{rq} \quad (14)$$

and the change of the rotational velocity of the rotor shaft in the DFIG-wind turbine can be represented by [24]:

$$J \frac{d}{dt} \omega_r = T_m - T_e \quad (15)$$

where J is the inertia constant of the wind turbine system and T_m the mechanical torque.

III. THE SCHEME TO SMOOTH THE OUTPUT POWER

To mitigate the fluctuation in the output power of the wind turbine, in this research the wind turbine must be operated in

the power control mode. To adjust the output active power of the wind turbine, we should adjust the i_{rq} component because by adjusting this component we can accommodate the torque (14) and hence the rotor velocity will be changed as in (15). As a result, the output active power will approach the desired value. In this research, we reuse the structure of RSC and GSC and utilize the controllers applied to RSC and GSC in [26]. The role of the RSC controller is to control the active power and the reactive power output of the wind turbine and the role of the GSC controller is to maintain a constant voltage on the DC-link and a zero reactive current output. However, the reference power of the RSC controller is modified. Principally, it must compensate the fluctuation in its actual active power. The average output active power of each wind turbine is calculated as [8]:

$$P_{o-av} = \frac{E}{T} = \frac{1}{T} \int_0^T P_o dt \quad (16)$$

where T is the time interval, $E = \int_0^T P_o dt$ is the electrical energy output of each wind turbine in the period T , P_o is the actual output power of each wind turbine, and P_{o-av} the average active power of each wind turbine in the period T .

The fluctuation in the output power can be calculated as:

$$\Delta P_{co} = P_o - P_{o-av} \quad (17)$$

ΔP_{co} varies around zero, it can be either positive or negative. When ΔP_{co} is negative it means that the actual output power is lower than the average output power, and hence the reference power should be increased. On the contrary, with a positive ΔP_{co} , the actual output power is over the average value so the reference power should be reduced. Hence, the power reference is defined by (18). Equation (18) indicates that the reference power of each wind turbine compensates the variation of the actual output power. This is the main idea of the proposed method.

$$P_{ref} = P_{mppt} - \Delta P_{co} \quad (18)$$

The reference power of the RSC controller is described in Figure 3(a). Figure 3(b) describes the reference power in the case of wind turbine using the EMA method [4, 13, 19].

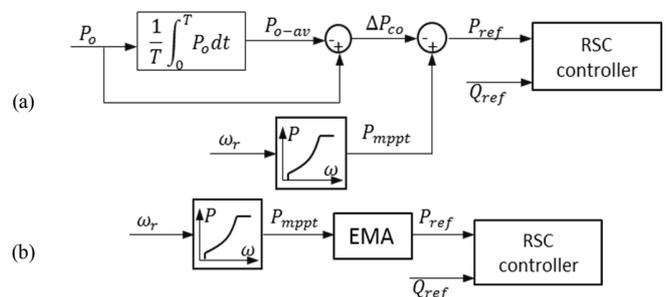


Fig. 3. Reference power for RSC controller: (a) Proposed method and (b) EMA method.

IV. RESULTS AND DISCUSSION

The Simulink environment in MATLAB software was used to simulate a group of two DFIG-wind turbines using the

proposed scheme in order to verify it. The details of some models are shown in the Appendix. The wind turbine capacity is 1.5MW and its power coefficient is described by (19) [23]:

$$C_p(\lambda, \beta) = 0.5176 \left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{-\frac{21}{\lambda_i}} + 0.0068\lambda \quad (19)$$

where:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.008\beta} - \frac{0.035}{\beta^3 + 1}$$

This wind turbine's characteristics are described in Figure 2. To simulate the wind turbine system, we assume the wind speed data presented in Figure 4. We use the DFIG parameters described in detail in [27].

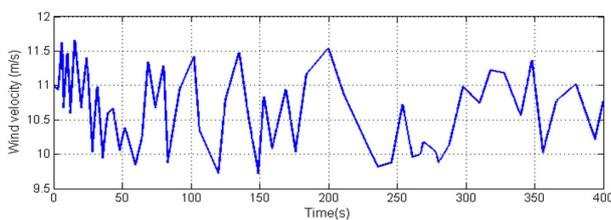


Fig. 4. Wind velocity data.

Here, we will compare the simulation results of the wind turbine group using the proposed method with the wind turbine group without any smoothing scheme (Original) and with the wind turbine group using the EMA method. The objective of the comparison to the original case is to verify the applicability of the proposed method to the wind turbines, whereas the comparison to the EMA method is to indicate the benefits of the proposed method.

A. Comparison with the Original Case

The main objective of this section is to verify and evaluate the efficiency of the proposed method. The simulation results will be compared to the original case, in which the wind turbines do not use any smoothing method or the ΔP_{Co} in Figure 3 is set at zero. The simulation results are shown in Figure 5. As can be seen from Figure 5, with the proposed method, the wind turbine group has a better performance than the original case. As can be seen from Figure 5(a), the variation range of the power output is mitigated significantly in comparison to the original case. Clearly, from 50s to 150s, in the original case, the output power varies from around 1.5MW to 2.1MW whereas with the proposed method, it varies between 1.6MW and 2MW. At around 245s, the output power is 1.47MW and 1.55MW corresponding to the proposed method and the original case. To obtain this power output, the amount of compensation power of each wind turbine is calculated as shown in Figure 5(b). With the proposed method, from 180s to 230s, the actual output power is higher than the average output power whereas from 230s to 310s, the actual output power is lower than the average output power. To compensate this difference, the reference power of each wind turbine, which is the input of the RSC controller, is shown in Figure 5(c). We can see that, by comparing to the original case, the reference power is lower in the period from 180s to 210s

and it is higher from 215s to 230s. Clearly, the continuous curve in Figure 5(c) is a little different to the summation of the broken curve in Figure 5(c) and the curve in Figure 5(b). The main reason is that the operation point of wind turbines is changed due to the reference output power.

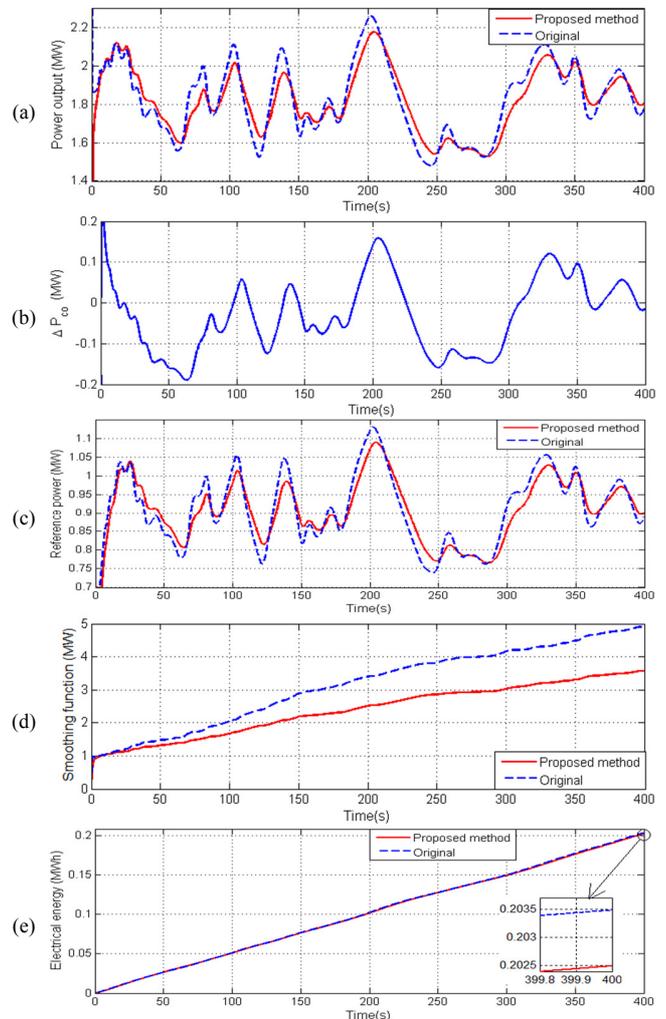


Fig. 5. Simulation results with the proposed method and the original case: (a) power output, (b) compensation power, (c) reference power, (d) smoothing function, and (e) electrical energy.

Figure 5(d) indicates the smoothing function of two cases. Obviously, with the proposed method, the smoothing function value is almost lower than that of the original case. At the end of the simulation period with the proposed method the smoothing function is around 3.58MW whereas with the original case it is around 5MW. Therefore, the proposed method can be completely utilized to reduce the fluctuation in the output power of the wind turbine group. Regarding the electrical energy output, Figure 5(e) shows that the proposed method makes the electrical energy output of the wind turbine group a little lower than that of the original case. However, the amount of decrease is insignificant. At the end of the simulation interval, the electrical energy output is 0.2025MWh and 0.2035MWh for the proposed method and the original case

respectively. It means only 1kWh is lost due to the application of the proposed method. In conclusion, by using the proposed method, the reference power supplying the RSC controller compensated the variation of the output active power and hence the output active power of the group wind turbine varies with a smaller range of that of the original case. It means we can use the proposed method to mitigate the variation of the output power of the wind turbine group.

B. Comparison to the EMA Method

The EMA method was used to smooth the output power of the wind turbine [4, 13, 19]. In this research, the EMA method is applied to wind turbines operating in the power control mode to determine the reference power (Figure 3(b)). The reference power is described as:

$$P_{ref}(t) = P_{ref}(t - T) + \alpha (P_{mppt}(t) - P_{ref}(t - T)) \quad (20)$$

where T is the time period and α is the smoothing factor of EMA, $0 < \alpha < 1$.

In this research, we use $\alpha=0.5$ and $T=20s$. The simulation results are shown in Figure 6.

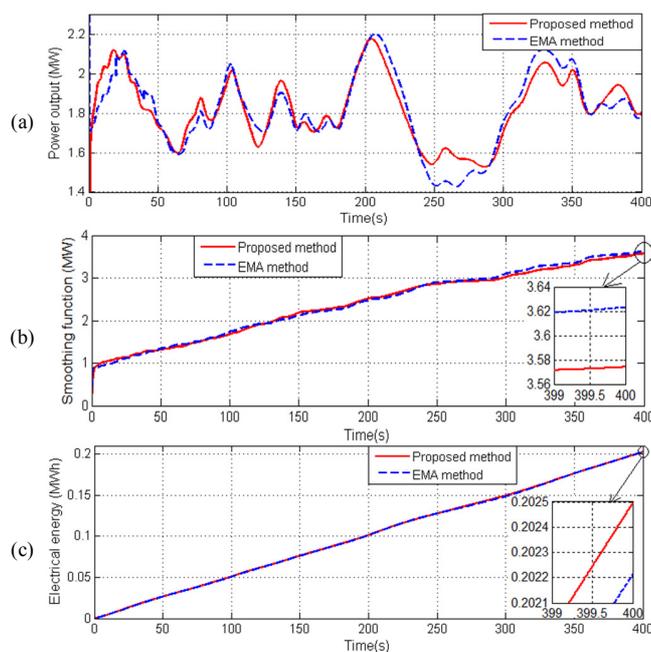


Fig. 6. Comparison between the proposed method and the EMA method: (a) power output, (b) smoothing function, and (c) electrical energy.

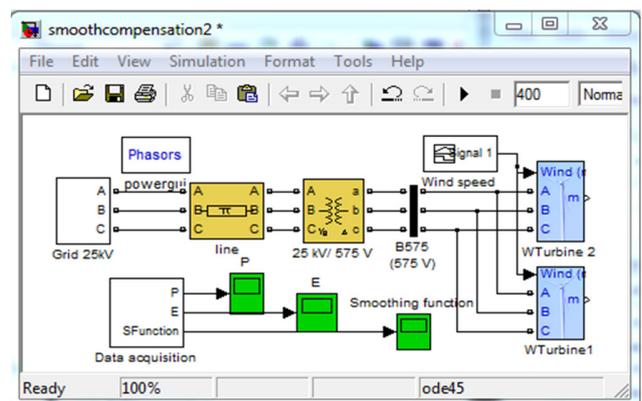
As can be seen from Figure 6(a), the output power of the wind turbine group using the proposed method is obviously smoother than that of the EMA method. Around 250s, with the EMA method, the output power is deeply reduced in comparison with that of the proposed method. By contrast, at the 330s, it becomes higher. Hence, the performance of the wind turbine group with the EMA method is not better than that with the proposed method. Figure 6(b) indicates the smoothing function value of the wind turbine group. As can be seen from this Figure, the smoothing function value with the

proposed method is lower than that with the EMA method. At the end of the simulation interval, they are around 3.58MW and 3.62MW for the proposed method and the EMA method respectively. Moreover, the electrical energy of the wind turbine group with the proposed method is a little higher than that with the EMA method. From Figure 6(c), the output electrical energy of the wind turbine group with the proposed method is 0.2025MWh whereas with the EMA method is 0.2022MWh at the end of the simulation interval. Therefore, the proposed method has a better performance than the EMA method.

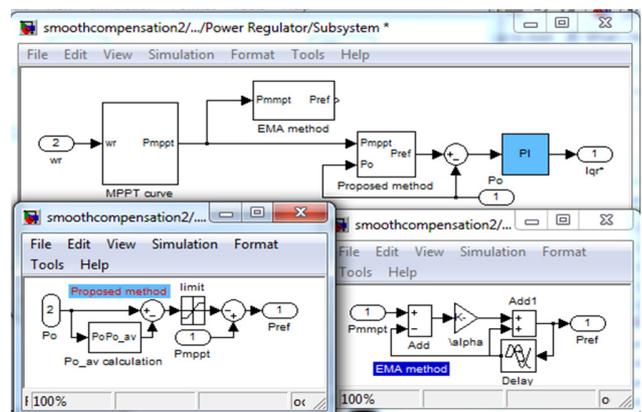
V. CONCLUSION

This research proposed a new scheme to mitigate the fluctuation in the output power of a wind turbine group without an energy storage system. In this research, the active power control mode is used in wind turbines, and the reference active power is calculated to compensate the difference between the average output power and the actual output power. The proposed method is verified and evaluated by in the Simulink environment of Matlab. The simulation results of the proposed method, the EMA method, and the original case were compared. The comparison indicated that when using the proposed method, the output power variation of the wind turbine group was mitigated significantly, and its performance is better than that of the EMA method.

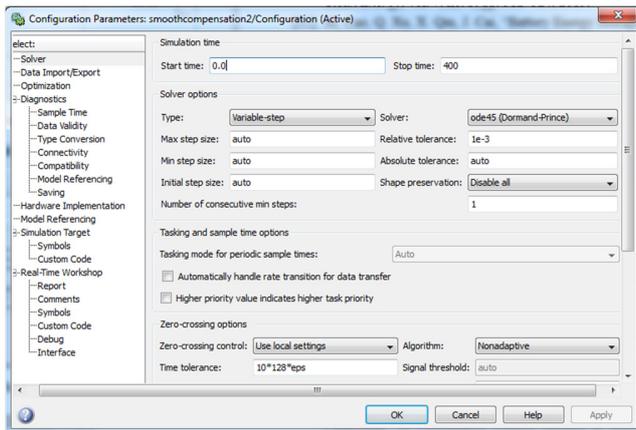
APPENDIX



General model of the proposed method.



Reference power calculation.



Simulation settings.

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