

Received November 6, 2020, accepted November 21, 2020, date of publication November 26, 2020, date of current version December 9, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3040905

Enhanced Low-Voltage Ride-Through Coordinated Control for PMSG Wind Turbines and Energy Storage Systems Considering Pitch and Inertia Response

CHUNGHUN KIM¹, (Member, IEEE), AND WONHEE KIM², (Member, IEEE)

¹Department of AI Electrical Engineering, Pai Chai University, Daejeon 35345, South Korea

²School of Energy Systems Engineering, Chung Ang University, Seoul 06974, South Korea

Corresponding author: Wonhee Kim (whkim79@cau.ac.kr)

This work was supported by the Energy Cloud Research and Development Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT, under Grant NRF-2019M3F2A1073313.

ABSTRACT Low-voltage ride-through (LVRT) requirements are defined by grid operators, and they vary based on power system characteristics. Coordinated LVRT control methods have been proposed for wind turbines (WTs) and energy storage systems (ESSs). ESSs can successfully help achieve LVRT by regulating DC-link voltage during a grid fault. During LVRT, WTs cannot transfer power to a grid because of their low voltage and current limit. Moreover, as grid operators typically require reactive power support during a grid fault, active power cannot be properly transferred to the grid. This results in fluctuation in the DC-link voltage in wind power generators and it can induce significant damage in the systems. ESS have been used for achieving better LVRT response to protect WT systems and meet LVRT grid requirements. Previous coordinated control methods have mainly focused on DC-link voltage regulation based on ESS charging and discharging control. As ESSs have high installation cost and limited charging capacity, it is better to coordinate the LVRT response properly considering the state of charge of ESSs and the rotor speed and pitch angle of WTs. In this work, an enhanced coordinated LVRT control method is proposed based on a fuzzy-logic algorithm. Fixed torque of the rotor control and a fixed ramp rate of the pitch control are employed for power analysis which is used in formulating fuzzy-logic controller. The effectiveness of the proposed method is validated by modeling a WT and an ESS topologically and performing simulations using the MATLAB/Simulink SimPowerSystems toolbox.

INDEX TERMS Enhanced coordinated controller, DC link voltage, energy storage system, fuzzy-logic controller, rotor inertia, low-voltage ride-through, rotor speed limitation, pitch angle control.

I. INTRODUCTION

The usage of wind power (WP) has increased in recent years. However, this has resulted in several issues in the integration of WP in power systems. There are several different types of wind power systems (WPSs). Permanent magnet synchronous generator (PMSG) wind turbines (WTs) are one of the widely used WPSs. Other WPSs include doubly fed induction generator (DFIG) WTs and variable speed WTs. However, PMSG WTs provide several advantages over DFIG WTs. The major advantage of a PMSG WT is its

large operation range because it fully uses power converters, i.e., machine-side converters (MSCs) and grid-side converters (GSCs) [1]–[3]. Advanced power converter control methods are necessary for effectively utilizing this advantage [4]. These methods enable WPSs to generate the maximum WP [5] and control active and reactive power according to power grid conditions.

As WP capacity is increasing, the integration issues of WP have become more important. There are multiple integration issues in WPSs such as wind power fluctuation, LVRT, and the forecasting and scheduling of WP according to wind conditions. For the reliable and economic operation of a WPS according to power grid conditions, it should switch its

The associate editor coordinating the review of this manuscript and approving it for publication was Mahdi Pourakbari Kasmaei¹.

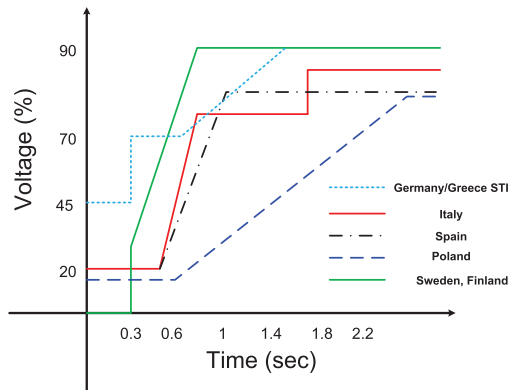


FIGURE 1. Limit curves for voltage to allow generator disconnection.

operation between maximum power production and grid support [6], [7]. Each type of operation is important for several reasons. LVRT is one of the main issues in the reliable and stable operation of WPSs, even in a grid fault condition. During a low-voltage fault, the active power from a WPS is reduced owing to low grid voltage and its current limit. Moreover, a WPS should produce a certain amount of reactive current according to its grid code [8]. Owing to the reduction in grid voltage and the reactive current requirement, WP cannot be transferred to the grid properly and is stored in a DC-link capacitor. Consequently, DC-link voltage is increased. This can result in the undesirable control response of the WPs. Thus, to protect a WT and provide reactive current to the power grid during a grid fault, an LVRT control method is required with or without the use of additional devices. Grid operators require WTs to remain connected to a grid when grid voltage sags; this is important for integrating a WPS with a grid. As shown in Fig. 1, grid operators have different grid codes, which define grid requirements in the case of a grid voltage event.

To enhance LVRT response, many LVRT control methods have been introduced. For better transient response during a fault, a proportional-integral (PI) controller was designed for DC-link voltage regulation using current feed-forward methods and the impact of unbalanced voltage fault was discussed in [9]. By considering nonlinear dynamics of DC-link voltage, a nonlinear controller based on feedback linearization was introduced in [10]. To reduce its complexity, a feedback linearization based on sliding mode control algorithm was introduced [11]. It results in better performance and robustness of controller performance for parameter variations. The WT LVRT controller using an MSC and pitch angle was introduced in [12]. The researchers used a braking resistor to ensure that a WPS did not exceed its current limit or rotor speed limit during LVRT. An MSC was controlled for regulating DC-link voltage and GSC was controlled for active and reactive current supports during a fault in [13], [14]. In a few studies, additional devices were used for helping LVRT response. Among various active and reactive power supporting devices, energy storage system (ESS) is getting more interest for LVRT and other WP applications [6].

It can help WPS to be more stable and cost-efficient system by supporting its variability. The LVRT method of a direct-drive WPS using ESS control for DC-link voltage regulation was introduced [15]. LVRT methods using an ESS in wind power plant were introduced to support voltage restoration at the point of common coupling (PCC) during grid fault [16], [17]. In [18], a non-linear adaptive control for the ESS embedded dynamic voltage restorer in enhancing the LVRT capability of wind power plant. An optimal reactive power control method considering cost reduction was introduced in [19]. A coordinated control method of WPS and ESS was introduced in [20]. However, the method did not consider the pitch control action of WPS.

In this study, we propose an enhanced coordinated fuzzy-based LVRT method considering the inertial response capability and pitch angle control response of a WT in addition to the SoC of an ESS. Previous fuzzy-based LVRT methods focused only on the rotor inertia response of a WT and an ESS SoC operation limit. However, pitch angle control can significantly affect LVRT response, particularly at high wind speed. Previous studies focused on high wind speed conditions because they can result in undesirable response according to the limit of the rotor speed of a WT and the SoC of an ESS. In high wind speed conditions, the rotor speed is close to the rated speed and there is a small amount of reserve energy in the form of rotor inertia. The ESS SoC can vary with time, and it might contain a small amount of reserve energy for charging at the moment of a grid fault. To handle this issue and obtain more reserve energy for LVRT, we included pitch angle control response in fuzzy-based LVRT control. We analyzed reserve energy based on pitch angle control and rotor inertial response. We used fixed torque control in rotor and fixed ramp rate control in pitch system. The fixed torque control value is determined through fuzzy-logic controller considering reserve energies of a WT and an ESS. We validated the effectiveness of the proposed method by performing simulations using the MATLAB/Simulink SimPowerSystems toolbox considering a topological circuit model. The simulation results show that the proposed method effectively achieves reliable operation without violating constraints. The benefits of the proposed method over previous fuzzy-based LVRT methods are as follows.

- The proposed method can enhance LVRT response by ensuring more stable operation with additional reserve energy through pitch angle control.
- LVRT response is a combination of pitch angle and rotor speed controls, and it is formulated using fuzzy-based control by analyzing total reserve energy of WPS.
- The reserve energy of a WT is analyzed based on the combined control response with fixed torque control in rotor and fixed ramp rate control in pitch angle.

II. PMSG WPS

The mechanical power model of the WTs and the electrical power model of MSC and GSC are discussed in this section.

Moreover, we consider the DC-link voltage model of converter system. Lastly, the ESS model is described to consider the SoC of the ESS.

A. MECHANICAL POWER OF WTs

The mechanical power of the WTs can be evaluated by considering some WT parameters and wind speed. These WT parameters are power coefficient, C_p , tip speed ratio, λ , pitch angle, β , and blade swept area, A . C_p is obtained from the performance experimental data and λ is defined using rotor speed, ω_m , rotor radius, R , and wind speed, v_{wind} . The tip speed ratio can be described by following Equation.

$$\lambda = \frac{\omega_m R}{v_{wind}}, \quad (1)$$

Thus, the value of tip speed ratio is proportional to rotor speed and rotor radius and inverse proportional to wind speed. WT can produce maximum available power at the optimal tip speed ratio, which is a fixed value according to WTs. The mechanical power of WTs can be evaluated by using these parameters as following Equation [12].

$$P_t = \frac{1}{2} \rho A C_p(\lambda, \beta) v_{wind}^3, \quad (2)$$

where ρ denotes the air density. Therefore, WT mechanical power can be produced by controlling λ and β . By controlling these values, WT mechanical power can be modulated to any power less than the maximum available WP which is decided by a given wind speed.

B. MSC MODEL

Mechanical power of WT is translated into electrical power from PMSG by controlling MSC. Since the electrical power of MSC has an effect on rotor speed, MSC control is important to modulate both electrical and mechanical powers. The PMSG voltage, current equations and electrical torque and rotor speed dynamics can be described as follows [14].

$$\begin{aligned} v_{dg} &= R_s i_{dg} + L_s \frac{di_{dg}}{dt} - \omega_s L_s i_{qg}, \\ v_{qg} &= R_s i_{qg} + L_s \frac{di_{qg}}{dt} + \omega_s L_s i_{dg} + \omega_s \lambda_f, \\ T_e &= \frac{3}{2} p \lambda_f i_{qg}, \\ T_m - T_e &= J \frac{d\omega_m}{dt}, \end{aligned} \quad (3)$$

where v_{dg} and v_{qg} indicate the stator dq axis voltages, and i_{dg} and i_{qg} indicate the stator currents of the PMSG. L_s and R_s indicate the stator inductance and resistance, respectively. ω_s indicates the rotor flux electrical speed. ω_m indicates the mechanical rotor speed. λ_f indicates the rotor flux. p indicates pole pairs of the machine. T_e and T_m indicate the electromagnetic and mechanical torques, respectively. J is the rotor inertia. From above equation, both the WP power and torque can be obtained. By controlling MSC, electrical torque and mechanical rotor speed can be modified.

C. GSC MODEL

The GSC can modulate power translation to grid side and the dynamic model can be illustrated as follows.

$$\begin{aligned} v_d &= v_{id} - R i_d - L \frac{di_d}{dt} + \omega L i_q, \\ v_q &= v_{iq} - R i_q - L \frac{di_q}{dt} + \omega L i_d, \end{aligned} \quad (4)$$

where L and R indicate the grid side line inductance and resistance, respectively; v_d and v_q indicate the grid side DQ-axis voltages. i_d and i_q indicate the grid side DQ-axis currents. v_{id} and v_{iq} are the GSC DQ-axis voltages. The DQ-axis rotating reference frame is assumed to be aligned with the grid voltage which is already introduced in [21].

$$\begin{aligned} P_{grid} &= \frac{3}{2} v_d i_d, \\ Q_{grid} &= \frac{3}{2} v_d i_q, \end{aligned} \quad (5)$$

where P_{grid} and Q_{grid} denote the active and reactive powers, respectively.

D. DC-LINK VOLTAGE MODEL

A DC-link voltage regulation is important for controlling both MSC and GSC, which is described as following equation [13].

$$P_c = C V_{dc} \frac{dV_{dc}}{dt} = P_g - P_{grid}, \quad (6)$$

where P_g and P_{grid} indicate the power of the MSC and GSC, respectively; P_c is the power stored in the DC-link and it is determined by the difference between MSC and GSC powers. C is the DC-link capacitor. V_{dc} indicates DC-link voltage.

E. ESS MODEL

ESS is used for voltage regulation in WPs application and it gives good performance when the ESS has enough reserve operation ranges for charging and discharging. Unfortunately, ESS has operation constraints as the SoC should remain between 0 to 1. Thus, it is better to consider ESS SoC for stable and efficient operation. In this section, we described the ESS power reference of the conventional DC-link regulation method and the way how the SoC is evaluated. Conventional ESS power reference can be defined by following equation.

$$P_{ESS}^* = K_P (V_{dc}^* - V_{dc}) + \int K_I (V_{dc}^* - V_{dc}) \quad (7)$$

P_{ESS}^* is the ESS power reference for DC-link voltage regulation. This ESS power reference is defined based on the error of DC-link voltage and its PI control. Since it does not consider ESS SoC and it can induce severe problem when the ESS SoC reaches to its constraints values. Therefore we proposed fuzzy-based method considering ESS SoC and WP response including rotor inertia and pitch angle controls. The details of the proposed method is described in the next section. After measuring ESS power, the SoC can be evaluated as following equation.

$$W_{ESS}(t) = \int_0^t P_{ESS}(u) du + W_{ESS}(0) \quad (8)$$

$$SoC(t) = W_{ESS}(t) / W_{Max} \quad (9)$$

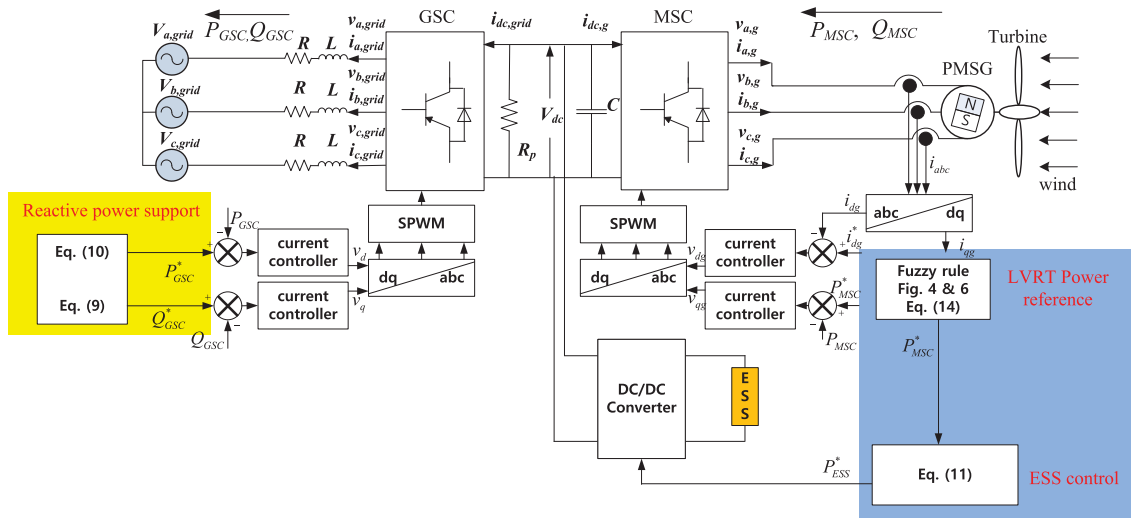


FIGURE 2. Overall control block diagram of the proposed method.

W_{ESS} and W_{Max} are the ESS energy and the maximum ESS energy capacity, respectively.

III. PROPOSED LVRT CONTROL SYSTEM

To coordinate the control of WT and ESS during a grid fault, we considered rotor inertia and pitch angle controls of WT. Pitch angle control is significant impact on LVRT response especially in high wind speed. We use the fixed ramp rate control in pitch angle and fixed torque control in rotor inertia control. From these control methods, we defined modified power coefficient which is varying with time. By using modified power coefficient, a maximum available reserve energy from WT is evaluated. We use this value and SoC in fuzzy-logic controller to obtain the MSC power reference during a grid fault. Therefore, rotor inertia and pitch angle controls are included for coordinating with ESS control. The overall control structure is illustrated in Fig. 2.

A. GSC ACTIVE AND REACTIVE POWER REFERENCES

In proposed method, GSC controls active and reactive power. During grid voltage fault, grid code requires reactive power support according to grid voltage condition. Thus, the reactive power support is more important than active power control. The reactive power reference is defined by following equation.

$$\begin{aligned} I_{q,GSC}^* &= 2V_{sag}, \quad (\text{for } I_{q,GSC}^* \leq 1 \text{ pu}) \\ Q_{GSC}^* &= I_{q,GSC}^* V_d, \end{aligned} \quad (10)$$

where $I_{q,GSC}^*$ denotes the reactive current reference according to the grid voltage sag, V_{sag} . Q_{GSC}^* is the reactive power reference, which is obtained from $I_{q,GSC}^*$ and the grid d-axis voltage, V_d . In Eq. 10, the GSC supports full reactive current when the grid voltage sag is larger than 50% as numerous grid codes required to WT [8]. After defining reactive power reference, the active power reference is defined considering

maximum current constraint.

$$\begin{aligned} I_{d,GSC}^* &= \sqrt{1 - (I_{q,GSC}^*)^2}, \\ P_{GSC}^* &= I_{d,GSC}^* V_d, \end{aligned} \quad (11)$$

where, $I_{d,GSC}^*$ denotes the active current reference. P_{GSC}^* is the active power reference.

B. FUZZY-LOGIC-BASED LVRT CONTROL OF MSC AND ESS

The ESS and WT MSC powers references can be obtained from the GSC power reference, according to the following relationship.

$$P_{MSC}^* + P_{ESS}^* = P_{GSC}^*, \quad (12)$$

where P_{MSC}^* and P_{ESS}^* denotes the MSC and ESS discharge power references, respectively. We can obtain ESS reserve power from its SoC and fault time duration. The fault time duration is defined by grid codes, and it differs according to grid codes. The reserve energy capacity of rotor inertia, E_{iner} can be obtained using following equation.

$$E_{iner} = \frac{1}{2} J (\omega_{m,max}^2 - \omega_m^2), \quad (13)$$

E_{iner} is determined from the rotor inertia, J , and the rotor speed, ω_m . And we can also obtain the total energy generation of WT, E_{WT} , as follows.

$$E_{WT} = \int_{t_1}^{t_2} P_t dt, \quad (14)$$

where, t_1 and t_2 denote the times when the grid fault occurs and clears, respectively. To simplify the calculation of the E_{WT} , the WT torque is controlled to be constant value and the acceleration of rotor speed is fixed. The pitch control system is activated when the sum of E_{iner} and reserve energy of ESS, E_{ESS} is less than E_{WT} . Figure 3 shows that pitch control can help reduce the WT mechanical power and obtain more reserve energy during a grid fault. When there is no pitch

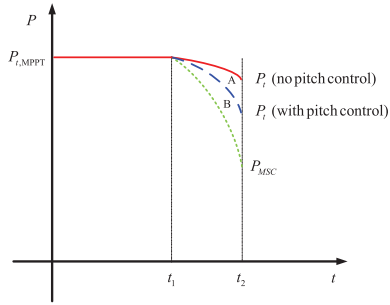


FIGURE 3. Analysis of combined pitch angle and rotor speed control response.

control action, the surplus energy corresponding to surface A and B is stored in rotor inertia and it induces rotor speed increase. However, when using pitch control, the surplus energy corresponds to surface B. Thus, it has more reserve energy (A surface) when using pitch angle control compared to that of when there is no pitch control. Ramp rate of pitch angle variation is fixed as 10 degree/s which is typical control value of a pitch system. From these conditions of rotor speed acceleration and ramp rate of pitch angle control, we can obtain the modified power coefficient from Eq. 2. Since the power coefficient is a function of rotor speed and pitch angle, it can be transformed as a function of time. The maximum available reserve energy of WT, E_{res} , can be obtained by increasing pitch angle and rotor speed to be maximum value.

$$E_{res} = \int_{t_1}^{t_2} (P_{t,mppt} - P_t^*) dt + E_{iner}, \quad (15)$$

where, P_t^* is the WP when the pitch angle is controlled to its maximum available value and $P_{t,mppt}$ is the MPPT power output which is the power produced in normal condition. Thus, we can obtain both reserve energies of WPS from Eq. 15 and reserve energy of ESS from SoC value. We use these two reserve energies in fuzzification process.

We can obtain the WP profile during a grid fault from the above equation. Additionally, we can obtain the required ESS energy capacity according to pitch angle and rotor speed controls. We formulated the enhanced coordinated fuzzy-based LVRT controller using the available reserve powers of the WT and ESS. We defined the input and output membership functions for fuzzy-logic control as shown in Fig. 4. Then, we utilized these membership functions to define fuzzy rule for the appropriate power management of the MSC and ESS, as shown in Fig. 5. The overall fuzzy-logic controller is described in Fig. 6. The maximum available reserve energy of WT and SoC membership functions were used to obtain fuzzy membership values, $\mu(E_{res})$ and $\mu(SoC)$.

IV. SIMULATION RESULTS

We validated the effectiveness of the proposed method by performing simulations using the MATLAB/Simulink SimPowerSystems toolbox. The parameters of the WP and ESS used in simulations are listed in Table 1. We compared the performance of the proposed method and a conventional method during a grid voltage sag of 80%, which implies

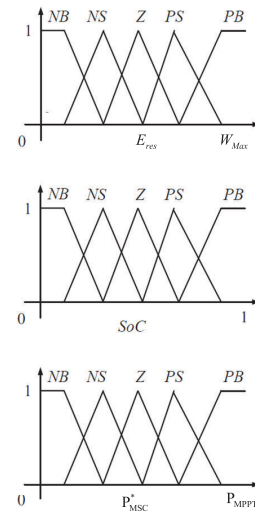


FIGURE 4. Membership functions of the proposed method.

	P_{MSC}^*				
	NB	NS	Z	PS	PB
NB	Z	NS	NS	NB	NB
NS	PS	Z	NS	NB	NB
Z	PS	PS	Z	NS	NS
PS	PB	PB	PS	Z	NS
PB	PB	PB	PS	PS	Z

FIGURE 5. Fuzzy rule of the proposed method.

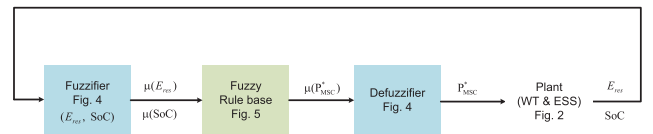


FIGURE 6. Fuzzy logic controller.

that the GSC should produce only reactive power and no active power. Conventional method is that both WT and ESS are controlled to dc link voltage regulation and does not consider about their operation limit during grid fault. It focused only on dc link voltage regulation during grid fault for stable operation, but does not consider how to coordinate and share the burden between WT and ESS. In conventional method, WPS has inertial response for LVRT, however, it does not consider the effective coordination with ESS control during grid fault. The grid fault occurred at 1 s, and grid voltage reduced to 20% of its nominal value. In this case, the PMSG WT should reduce its active power production to zero using the MSC and ESS LVRT controls. The conventional method used PI controller for the DC link voltage regulation, whereas the proposed method used fuzzy-based LVRT control. Firstly, we illustrated the simulation results of conventional method with and without usage of pitch control. We compared the results focusing on pitch control can reduce the burden of LVRT during a grid fault. Secondly, we compared the results between conventional

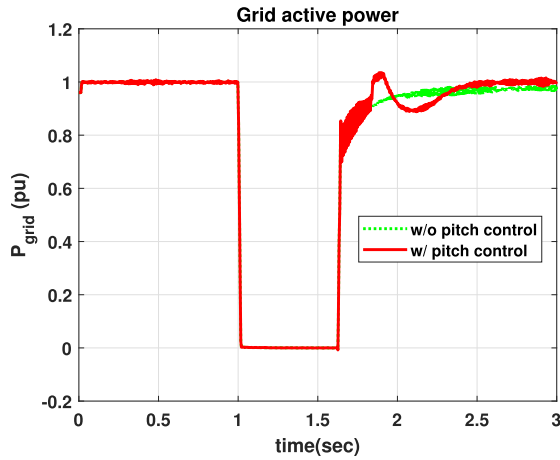


FIGURE 7. Grid active power during a balanced voltage sag (80%) using conventional LVRT method.

TABLE 1. System parameters used in simulation.

Parameter	Value	Unit
Rated power	1.63	MW
Rated wind speed	12	m/s
Max. power coefficient	0.5	
Optimal tip speed ratio	9.9495	
Blade radius	33.05	m
Air density	1.12	kg/m^3
Max. rotor speed	4.335	rad/s
DC-link voltage	1150	V
Turbine inertia	6500	kgm^2
ESS capacity	1	kWh

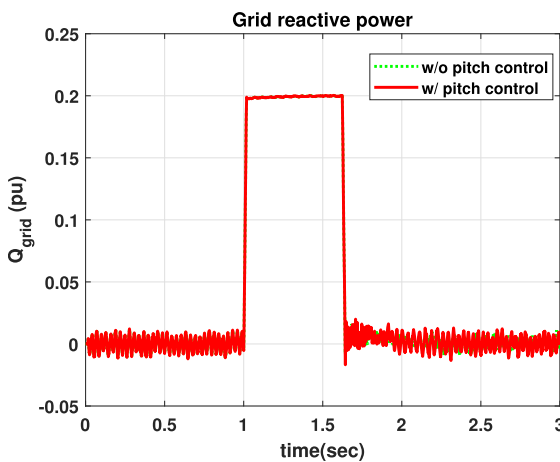


FIGURE 8. Grid reactive power during a balanced voltage sag (80%) using conventional LVRT method.

method and the proposed method. Both method has pitch control during a grid fault. From these two simulation results we illustrates the effectiveness of the proposed method. The proposed method effectively handled these cases with efficient power management of the WT and ESS during the grid fault.

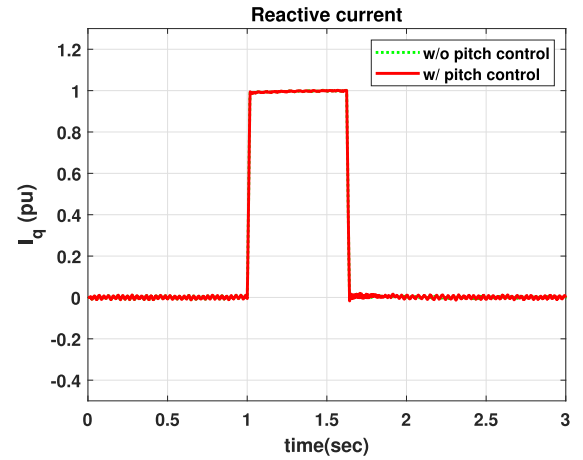


FIGURE 9. PCC q-axis (reactive) current during a balanced voltage sag (80%) using conventional LVRT method.

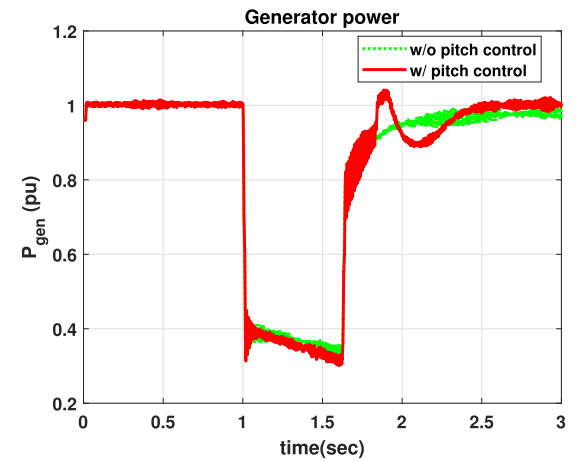


FIGURE 10. Generator active power during a balanced voltage sag (80%) using conventional LVRT method.

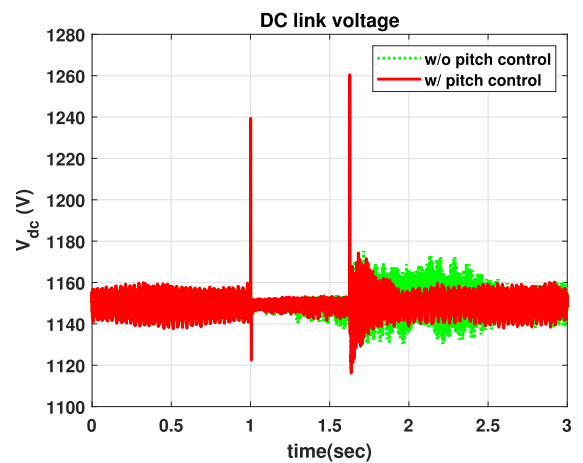


FIGURE 11. DC-link voltage during a balanced voltage sag (80%) using conventional LVRT method.

A. MOTIVATIONAL EXAMPLE

Several previous studies focus on the LVRT control of WT during a grid fault with and without the pitch angle control. Since the main contribution of this paper is inclusion of pitch

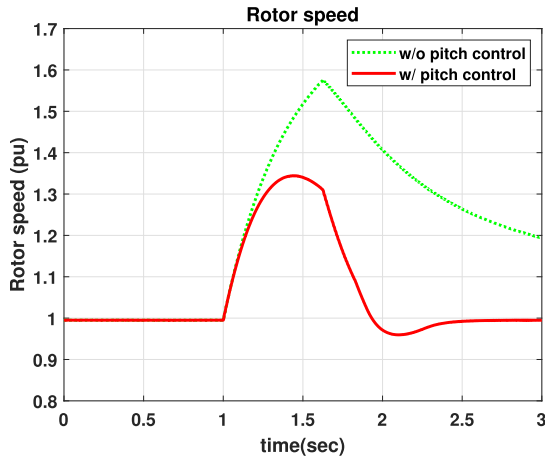


FIGURE 12. Rotor speed variation during a balanced voltage sag (80%) using conventional LVRT method.

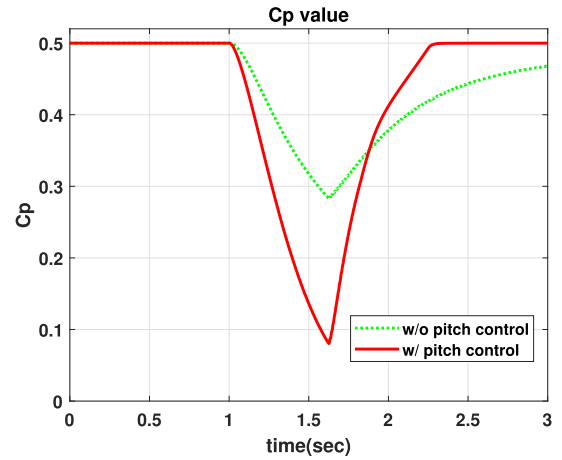


FIGURE 15. Power coefficient during a balanced voltage sag (80%) using conventional LVRT method.

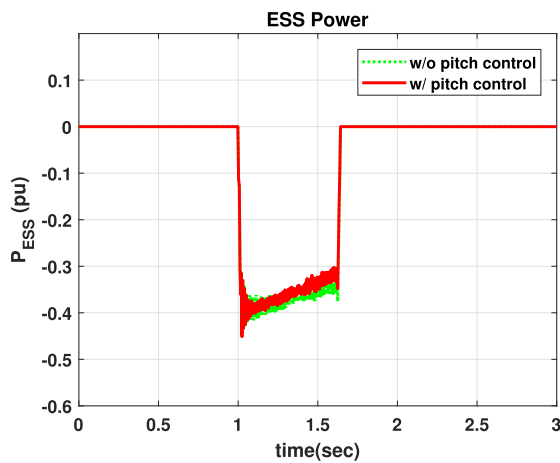


FIGURE 13. ESS power during a balanced voltage sag (80%) using conventional LVRT method.

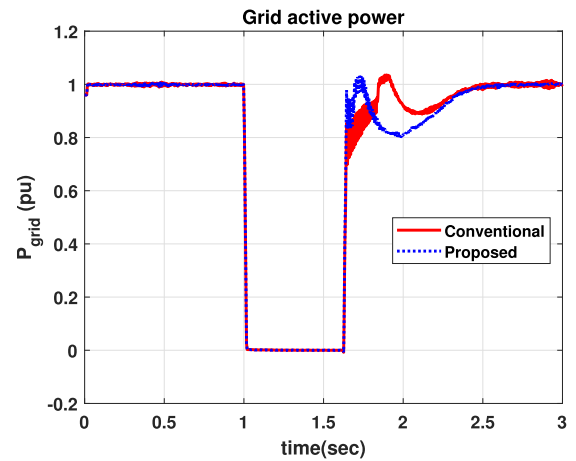


FIGURE 16. Grid active power during a balanced voltage sag (80%).

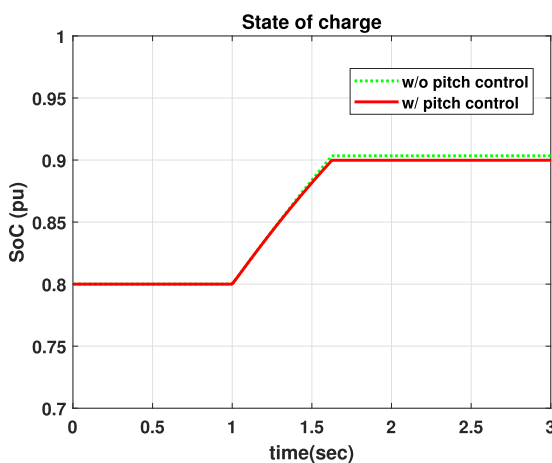


FIGURE 14. SoC during a balanced voltage sag (80%) using conventional LVRT method.

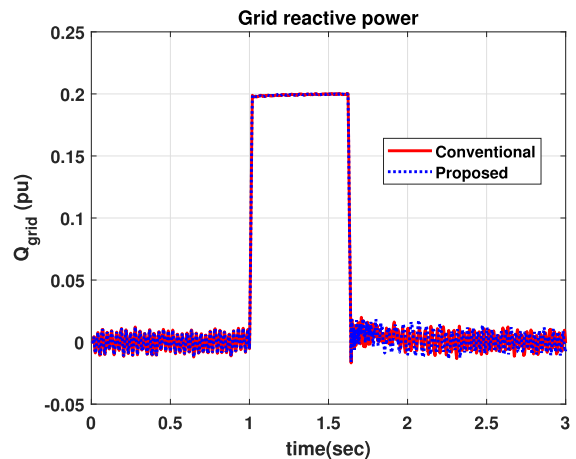


FIGURE 17. Grid reactive power during a balanced voltage sag (80%).

control in coordinated control of ESS and WPS, this section describes why the pitch angle control should be included to reduce the burden of inertia control and ESS control during

the grid fault. Rotor speed and ESS SoC level can be reduced due to pitch control. The pitch angle can change the power coefficient value and it has significant impact especially when there is high wind speed. Since energy management of WPS during a grid fault is important especially in high wind speed,

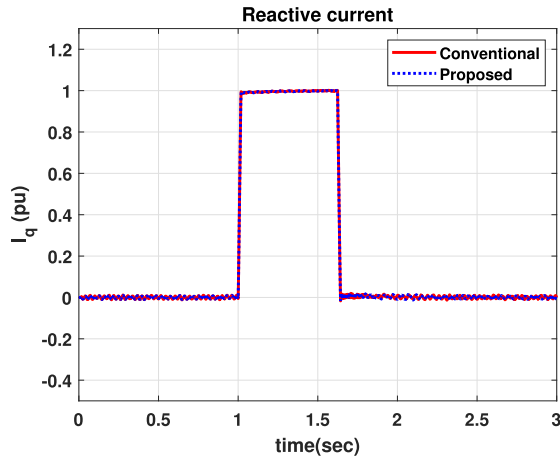


FIGURE 18. PCC q-axis (reactive) current during a balanced voltage sag (80%).

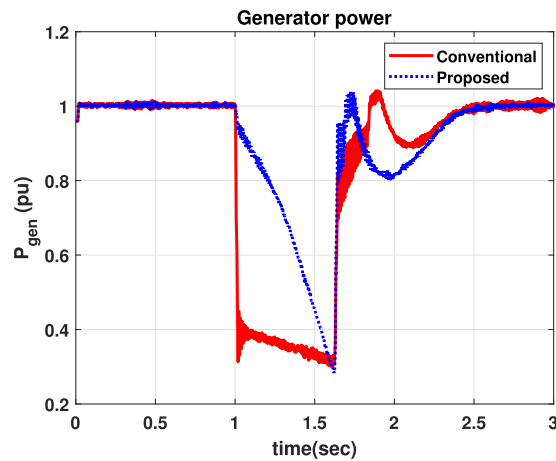


FIGURE 19. Generator active power during a balanced voltage sag (80%).

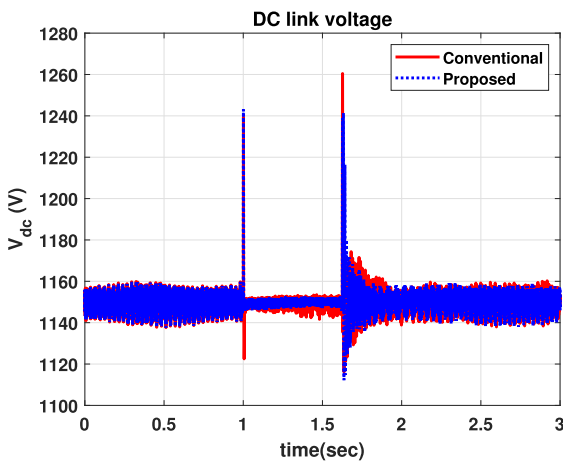


FIGURE 20. DC-link voltage during a balanced voltage sag (80%).

the pitch angle control can be effectively used. To illustrate this perspective, we simulated the LVRT response of the conventional method with and without the pitch control. Figure 7 shows that grid active power is reduced to zero and only reactive power is produced. As there is a voltage sag of 80%

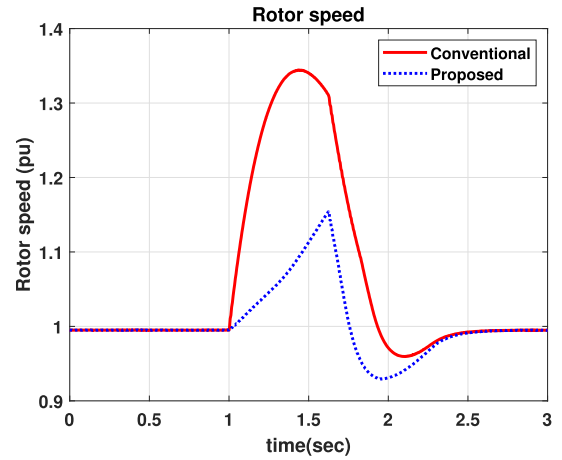


FIGURE 21. Rotor speed variation during a balanced voltage sag (80%).

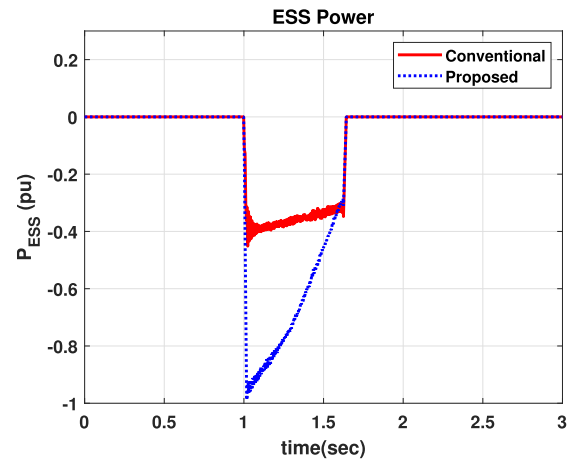


FIGURE 22. ESS power during a balanced voltage sag (80%).

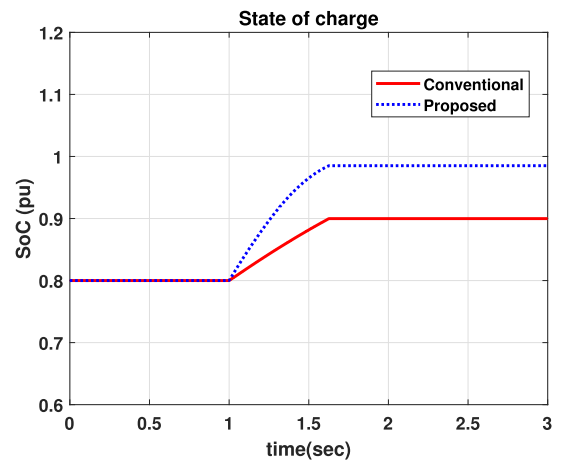


FIGURE 23. SoC during a balanced voltage sag (80%).

in the grid fault, reactive power is 0.2 pu for the full reactive current (1 pu) as shown in Fig. 8. Figures 9 illustrate the reactive currents during the grid fault. As the q-axis voltage is zero, q-axis currents are the active and reactive currents. As the voltage during the grid fault is 0.2 pu, reactive power is only 0.2 pu even though reactive current is as high as 1 pu. Both methods have similar response in reactive power since it

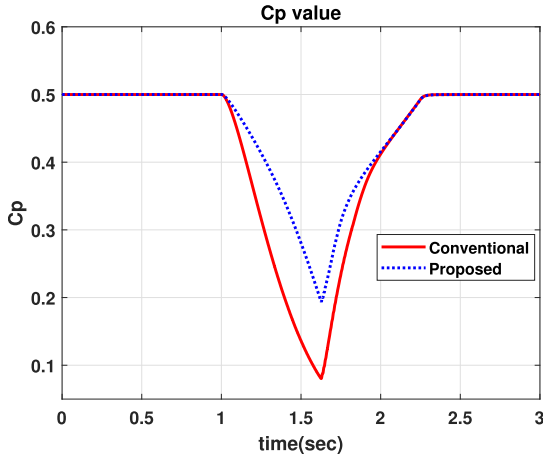


FIGURE 24. Power coefficient during a balanced voltage sag (80%).

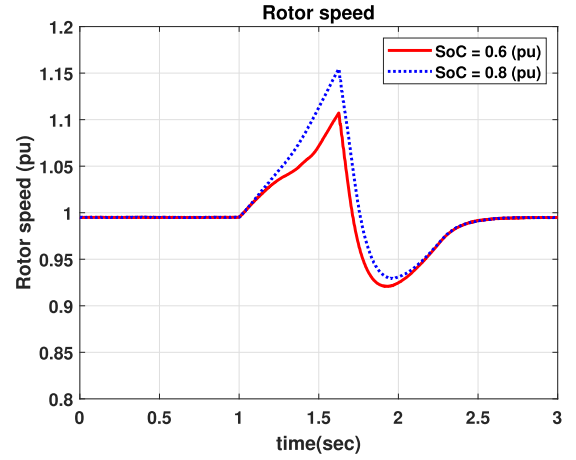


FIGURE 26. Rotor speed in the case study with different initial SoC values.

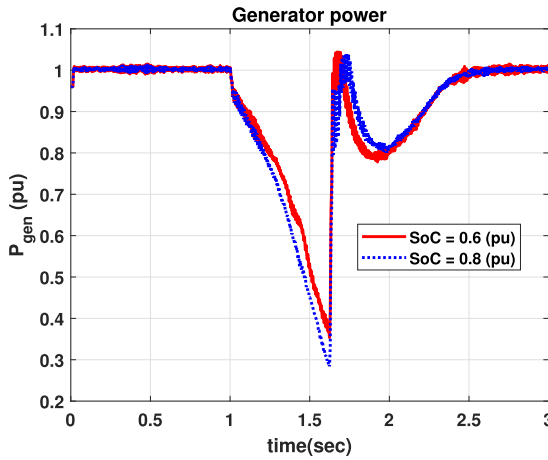


FIGURE 25. Generator power in the case study with different initial SoC values.

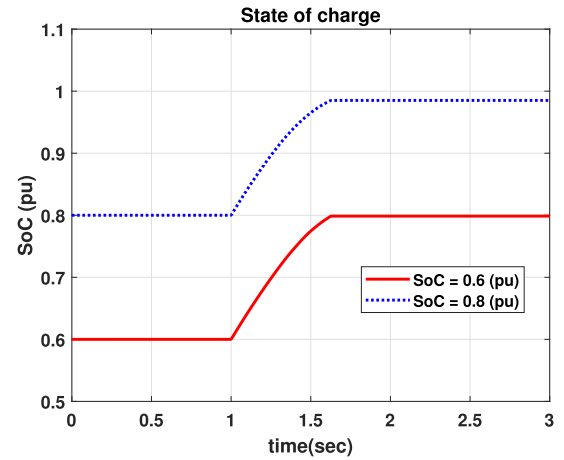


FIGURE 27. SoC profile in the case study with different initial SoC values.

only depends on GSC reactive power control. Active power is slightly different feather due to the pitch angle response during and after the grid fault. The generator power is less with pitch angle control during a grid fault as shown in Fig. 10. and it can be more advantageous for the LVRT. Figure 11 shows that both methods regulated DC-link voltage. However, it does not mean that both cases effectively handle LVRT since the rotor speed is violated as shown in Fig. 12. As shown in this figure, both methods violated maximum rotor speed (1.2 pu) during the grid fault. To solve this problem, control gain can be tuned. However it can induce other problems such as the ESS SoC reaches its maximum value or DC-link voltage can be significantly fluctuate. Thus it is difficult to find proper gain for LVRT. Figure 13 and 14 show that ESS power output and SoC variation, respectively.

Both methods have similar ESS power and SoC value during a grid fault. Figure 15 shows power coefficient of both cases and has less value when pitch angle control is employed. From these motivational simulation results, it is more efficient to employ pitch angle control especial in high wind speed during a grid fault and we compared the performance with the proposed method in the following section.

B. SIMULATION RESULTS OF PROPOSED METHOD

We compared the LVRT performance with conventional method with pitch angle control. The pitch angle control could help LVRT performance reducing LVRT burden in rotor inertia response as shown in previous section. However, it is hard to get proper gain of each control device such as rotor, pitch systems of WT and ESS. We simulated in the same grid fault condition as of previous section and compared the performances between the proposed method and the conventional method. Figure 16 shows that the grid active powers and has similar response during a grid fault. As there is a voltage sag of 80% in the grid fault, reactive power can be obtained as 0.2 pu for the full reactive current (1 pu), as shown in Fig. 17. Figure 18 illustrates the reactive currents during the grid fault. The GSC active and reactive powers obtained using the two methods are similar. However, the generator active powers are different in both methods since the proposed method is fixed torque control in the generator as shown in Fig. 19. Figure 20 shows that DC-link voltage and the proposed method has less voltage fluctuation compared to the conventional method. Figure 21 shows that the proposed method does not violate the constraint. Figure 22 shows that the ESS output power and has more charging value when

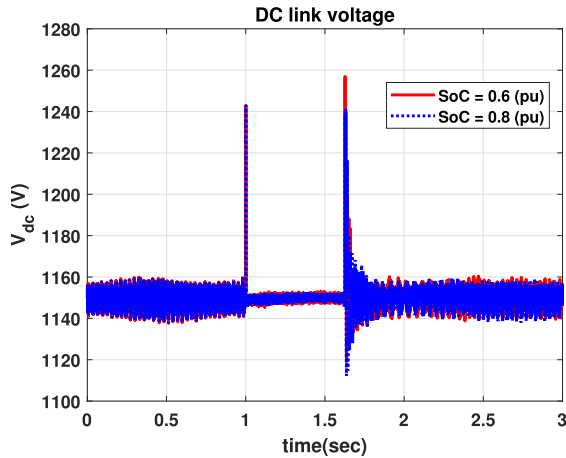


FIGURE 28. DC link voltage in the case study with different initial SoC values.

the grid fault occurs. Figure 23 describes ESS SoC and both method does not reach its maximum value as 1pu. Figure 24 illustrates power coefficient and the proposed method has a little bit large during a grid fault. Therefore, we obtained better performance of LVRT response from the proposed method ensuring the stable operation without complex gain tuning process. To understand the behavior of the proposed method with different condition, we changed the ESS SoC. We considered the case when the SoC value is reduced. Figures from Fig. 25 to Fig. 28 show that simulation results with different initial ESS SoC value. The generator power is increased since the ESS can charge more power when the ESS has lower initial SoC value as described in Fig. 25. Since large power is transferred to MSC, generator rotor speed has less peak value during grid fault as described in Fig. 26. The ESS SoC changes its value more when the initial SoC is 0.6 (pu) as described in Fig. 27. DC link voltage regulation performances are similar in both cases as described in Fig. 28. Therefore, The proposed method properly share the burden of LVRT in the case of different initial ESS SoC values. Similarly, the proposed method changes its operation when the wind speed is changed according to fuzzy-based LVRT algorithm.

V. CONCLUSION

We proposed an enhanced fuzzy-based LVRT method considering the rotor inertial response and pitch angle control of a WT and the reserve power of an ESS. Previous fuzzy-logic-based LVRT control considered the reserve energy stored in the rotor inertia of a WT and the ESS SoC. The proposed method achieved more stable LVRT control compared to conventional methods by adding pitch angle control and analyzing the combined response of pitch angle and rotor inertia controls in the WT. The WT provided more reserve energy during a grid fault by utilizing the proposed method. We formulated fuzzy-logic control by analyzing WP curve characteristics. The proposed method reduced the required energy capacity of the ESS and made the ESS more economically viable. We validated the effectiveness of

the proposed method by performing simulations using the MATLAB/Simulink SimPowerSystems toolbox considering topological circuit model. Simulation results showed that the proposed method achieved more stable LVRT response by providing more reserve power from the WT.

REFERENCES

- [1] H. Polinder, F. F. A. Van Der Pijl, G.-J. De Vilder, and P. J. Tavner, "Comparison of direct-drive and geared generator concepts for wind turbines," *IEEE Trans. Energy Convers.*, vol. 21, no. 3, pp. 725–733, Sep. 2006.
- [2] M. Chinchilla, S. Arnaltes, and J. C. Burgos, "Control of permanent-magnet generators applied to variable-speed wind-energy systems connected to the grid," *IEEE Trans. Energy Convers.*, vol. 21, no. 1, pp. 130–135, Mar. 2006.
- [3] Y. Gui, C. Kim, C. Choo Chung, J. M. Guerrero, Y. Guan, and J. C. Vasquez, "Improved direct power control for grid-connected voltage source converters," *IEEE Trans. Ind. Electron.*, vol. 65, no. 10, pp. 8041–8051, Oct. 2018.
- [4] Y. Gui, X. Wang, F. Blaabjerg, and D. Pan, "Control of grid-connected voltage-source converters: The relationship between direct-power control and vector-current control," *IEEE Ind. Electron. Mag.*, vol. 13, no. 2, pp. 31–40, Jun. 2019.
- [5] C. Kim, Y. Gui, and C. C. Chung, "Maximum power point tracking of a wind power plant with predictive gradient ascent method," *IEEE Trans. Sustain. Energy*, vol. 8, no. 2, pp. 685–694, Apr. 2017.
- [6] J. Kim, E. Muljadi, V. Gevorgian, and A. F. Hoke, "Dynamic capabilities of an energy storage-embedded DFIG system," *IEEE Trans. Ind. Appl.*, vol. 55, no. 4, pp. 4124–4134, Jul. 2019.
- [7] C. Kim, E. Muljadi, and C. Chung, "Coordinated control of wind turbine and energy storage system for reducing wind power fluctuation," *Energies*, vol. 11, no. 1, p. 52, Dec. 2017.
- [8] M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms," *IET Renew. Power Generat.*, vol. 3, no. 3, pp. 308–332, Sep. 2009.
- [9] G. Saccomando, J. Svensson, and A. Sannino, "Improving voltage disturbance rejection for variable-speed wind turbines," *IEEE Trans. Energy Convers.*, vol. 17, no. 3, pp. 422–428, Sep. 2002.
- [10] A. Mullane, G. Lightbody, and R. Yacamini, "Wind-turbine fault ride-through enhancement," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1929–1937, Nov. 2005.
- [11] J. Matas, M. Castilla, J. M. Guerrero, L. G. de Vicuna, and J. Miret, "Feedback linearization of direct-drive synchronous wind-turbines via a sliding mode approach," *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp. 1093–1103, May 2008.
- [12] J. F. Conroy and R. Watson, "Low-voltage ride-through of a full converter wind turbine with permanent magnet generator," *IET Renew. Power Gener.*, vol. 1, no. 3, pp. 182–189, Sep. 2007.
- [13] K.-H. Kim, Y.-C. Jeung, D.-C. Lee, and H.-G. Kim, "LVRT scheme of PMSG wind power systems based on feedback linearization," *IEEE Trans. Power Electron.*, vol. 27, no. 5, pp. 2376–2384, May 2012.
- [14] S. Alepuz, A. Calle, S. Busquets-Monge, S. Kouro, and B. Wu, "Use of stored energy in PMSG rotor inertia for low-voltage ride-through in back-to-back NPC converter-based wind power systems," *IEEE Trans. Ind. Electron.*, vol. 60, no. 5, pp. 1787–1796, May 2013.
- [15] W. Wang, B. Ge, D. Bi, M. Qin, and W. Liu, "Energy storage based LVRT and stabilizing power control for direct-drive wind power system," in *Proc. Int. Conf. Power Syst. Technol.*, Oct. 2010, pp. 1–6.
- [16] J. Liu, W. Yao, J. Fang, J. Wen, and S. Cheng, "Stability analysis and energy storage-based solution of wind farm during low voltage ride through," *Int. J. Electr. Power Energy Syst.*, vol. 101, pp. 75–84, Oct. 2018.
- [17] J. Yao, J. Li, L. Guo, R. Liu, and D. Xu, "Coordinated control of a hybrid wind farm with PMSG and FSIG during asymmetrical grid fault," *Int. J. Electr. Power Energy Syst.*, vol. 95, pp. 287–300, Feb. 2018.
- [18] L. Yan, X. Chen, X. Zhou, H. Sun, and L. Jiang, "Perturbation compensation-based non-linear adaptive control of ESS-DVR for the LVRT capability improvement of wind farms," *IET Renew. Power Gener.*, vol. 12, no. 13, pp. 1500–1507, Oct. 2018.
- [19] J. Li, N. Wang, D. Zhou, W. Hu, Q. Huang, Z. Chen, and F. Blaabjerg, "Optimal reactive power dispatch of permanent magnet synchronous generator-based wind farm considering levelised production cost minimisation," *Renew. Energy*, vol. 145, pp. 1–12, Jan. 2020.

- [20] C. Kim and W. Kim, "Coordinated fuzzy-based low-voltage ride-through control for pmsg wind turbines and energy storage systems," *IEEE Access*, vol. 8, pp. 105874–105885, 2020.
- [21] M. E. Haque, M. Negnevitsky, and K. M. Muttaqi, "A novel control strategy for a variable speed wind turbine with a permanent magnet synchronous generator," in *Proc. IEEE Ind. Appl. Soc. Annu. Meeting*, Oct. 2008, pp. 1–8.



CHUNGHUN KIM (Member, IEEE) received the B.S. degree in electronic electricity computer engineering and the M.S. and Ph.D. degrees from Hanyang University, Seoul, South Korea, in 2011 and 2018. In 2017, he was a Visiting Scholar with the National Renewable Energy Laboratory, Colorado, USA. In 2018, he was a Postdoctoral Researcher with the Department of Electrical Engineering, Kyungpook National University, Deagu, South Korea, where he worked as a Research Professor, in 2019. He is currently an Assistant Professor with the Department of AI Electrical Engineering, Pai Chai University, Daejeon, South Korea. His current research interests include integration of renewable energy and optimization of distributed energy resource in micro-grid.



WONHEE KIM (Member, IEEE) received the B.S. and M.S. degrees in electrical and computer engineering and the Ph.D. degree in electrical engineering from Hanyang University, Seoul, South Korea, in 2003, 2005, and 2012, respectively.

From 2005 to 2007, he was with Samsung Electronics Company, Suwon, South Korea. In 2012, he was with the Power and Industrial Systems Research and Development Center, Hyosung Corporation, Seoul, South Korea. In 2013, he was a Postdoctoral Researcher with the Institute of Nano Science and Technology, Hanyang University, Seoul, South Korea, and a Visiting Scholar with the Department of Mechanical Engineering, University of California, Berkeley, CA, USA. From 2014 to 2016, he was with the Department of Electrical Engineering, Dong-A University, Busan, South Korea. He is currently an Associate Professor with the School of Energy Systems Engineering, Chung-Ang University, Seoul, South Korea. He has served as an Associate Editor of *IEEE Access* and *Journal of Electrical Engineering and Technology*. His current research interests include nonlinear control and nonlinear observers, as well as their industrial applications.

...