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Enhancement of DFIG LVRT Capability During Extreme Short-Wind Gust Events Using SMES Technology

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ABSTRACT Wind energy is one of the premier renewable energy sources that have gained popularity during the last decade. Among the currently available wind energy conversion systems (WECS), doubly fed induction generator-based technology has been widely employed due to its superior advantageous. The key features of the DFIG-based WECS include its ability to capture more wind energy and support the grid with large reactive power during short disturbance events. On the other hand, DFIG is very sensitive to grid faults which affect its fault ride through (FRT) capability. Furthermore, extreme wind gust even for short durations may lead to the violation of the low voltage ride through (LVRT) threshold limits set by worldwide transmission line operators. This situation cannot be mitigated by the turbine blades pitch controller since the response of the pitch mechanical control is much slower than the rapid dynamic change in the wind speed during short duration of wind gust events. While DFIG FRT capability has been discussed in several papers in the literature, not much attention was given to the mitigation of the effects of extreme wind gust of short duration on the DFIG performance. In this paper, the effect of various levels of wind gust on the performance of a DFIG-based wind energy conversion grid-connected system is investigated and mitigated using a new controller for superconducting magnetic energy storage (SMES) unit. A combination of hysteresis current and fuzzy logic controllers is employed to control the voltage source converter and the DC-DC chopper interfacing the SMES coil with the investigated system. Simulation results reveal the effectiveness of the proposed SMES controller that can be easily implemented within existing as well as new WECS installations.

INDEX TERMS Doubly fed induction generator, low voltage ride through, superconducting magnetic energy storage, wind gust.

I. INTRODUCTION

Fossil fuel-based power plants are considered among the main sources of global warming. This has urged most of the nations to set plans to adopt more renewable-based electric power generation. Wind has been considered as one of the premier renewable energy sources that generated about 597 GW of the global power demand by the year 2018 [1], which is expected to increase to 29600 TWh by the year 2050 [2]. Because of its superior features, doubly fed induction generator (GFIG) has dominated the market of the wind energy conversion systems (WECS) [3]. However, due to the intermittent characteristics of wind speed, DFIG generated power may exhibit oscillations which in some cases can result in system instability [4]. As such, several mitigation and control techniques have been implemented to overcome

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this issue. Pitch control is a mechanical control mechanism that adjusts the wind turbine blades during wind speed fluctuation [5]. However, pitch angle calculation exhibits an error of about 0.5 degree due to manufacturing tolerance which affects the overall performance of the pitch control system [6]. Moreover, during extreme wind gust of short duration, the pitch control system, which is usually implemented using a hydraulic mechanism, is much slower than the rapid change in the wind speed [7].

Wind gust is classified when wind speed becomes more than 25 m/s for a short duration. As reported in [8], some countries in Europe have experienced extreme wind gusts with a recorded wind speed in the range 25 to 50 m/s. The pitch control system does not perform during such wind gust events which may lead to severe electrical and mechanical consequences [9]. Modern WECS have been equipped with a braking mechanism to lock up the blades during such event to avoid any mechanical damages [7]. While this protection mechanism is suitable for mid to long durations of wind gust, it is not effective for wind gust of short duration [4]. Moreover, the brake system that functions to stop the blades from rotating during wind gust has been identified as one of the WECS components that usually encounters a significant failure rate [10].

While several studies have been conducted to investigate the performance of WECS during grid faults and disturbance events, not much attention was given to investigate the impact of severe wind gust and propose a mitigation technique. In the early of 1997, performance of WECS under a wind gust event was investigated [11]. However, the investigated system was a standalone WECS of a small capacity in which a battery storage was proposed to stabilize the generated power. In [12], a small scale WECS is studied under a wind gust condition. However, the paper focused on capturing the wind gusts using an active filter without studying the impact of high speed wind on the performance of the WECS. A simulation of a micro-grid comprising WECS and PV during extreme operating gusts is presented in [13]. However, the turbine blades pitch control is not considered in the simulation model which is not recommended for real modern and large WECS. In [14], a maximum power point strategy is proposed to capture the energy of wind gusts.

In [15], a fuzzy control-based approach is used to maximize the wind power extraction without using a FACTS device. A hybrid-maximum power point tracker using artificial neural network is presented in [16]. Mossad *et al.* [17] presented a fractional order proportional integral controller for a WECS equipped with a high temperature superconducting coil placed in the DC link of the DFIG converters. These control approaches are only suitable for new WECS installations as they call for a modification to the WECS infrastructure. For existing WECS, connecting an external FACTS device with a proper controller is the most suitable technique to improve the overall performance of the system under various grid faults, disturbance and wind gust events [18].

Several flexible AC transmission systems (FACTS) with different control approaches have been proposed to improve the overall performance of WECS [18]. The applications of FACTS devices such as static synchronous compensator (STATCOM) [19], [20], static voltage compensator (SVC) [21] and unified power flow controller (UPFC) [22], [23] in WECS have been introduced in the literatures. For instance, a STATCOM with prominent control algorithm using proportion-integral (PI) and fuzzy logic controllers is introduced in [17]. Liu, et al introduced an application of the STATCOM on type-4 WECS considering under voltage load shedding [18]. In [24], SVC and super-capacitor are incorporated to mitigate the overvoltage in a micro grid comprising WECS and hydro generator units. A UPFC is introduced in [25] to mitigate the sub-synchronous resonance in series-compensated wind farms.

From the above brief literature review, it can be observed that not much attention was given to investigate and mitigate the impact of extreme wind gust on the ability of DFIG-based WECS to comply with the LVRT codes set by different countries. For instance the investigation in [26] focused only on the improvement of the design structure of the turbine blades to adapt during high wind speed of long to mid durations. A mathematical model of a hybrid system comprising wind turbine, photo voltaic and battery storage during wind gust event is presented in [11]. In [27], an optimal algorithm that facilitates a soft-cut out mechanism during a storm event is presented but the algorithm does not consider the voltage profile at the point of common coupling (PCC). The application of superconducting magnetic energy storage (SMES) unit in HVDC systems has been introduced in [28]. High temperature superconducting coil connected to the DC-link of the DFIG converters is introduced in [17] to enhance the overall performance of WECS. As mentioned above, this strategy is only suitable for new installation of DFIG-based WECS. However, there are several existing DFIGs installed worldwide with traditional control mechanism which call for external FACTS to support the system during disturbance and wind gust events.

As such, there is a research gap on investigating the impacts of the wind gusts of short durations on the performance of the WECS and the LVRT of the DFIG. Moreover, no mitigation technique for such events has been proposed in the literature yet. This paper is aimed to fill this research gap by presenting a detailed investigation to the effect of wind gusts of various levels on the LVRT of the DFIG. SMES technology is employed as a mitigation technique to control the effects of such events. Various commercial applications of the SMES technology in power systems has been comprehensively presented in [29]. This paper is also meant to add a new application of the SMES unit to mitigate the adverse effects of wind gusts of short duration on the performance of WECS. In this regard, the proposed SMES controller is divided into two parts; hysteresis current controller (HCC) and fuzzy logic controller (FLC) to respectively control the voltage source converter (VSC) and the DC-DC chopper interfacing

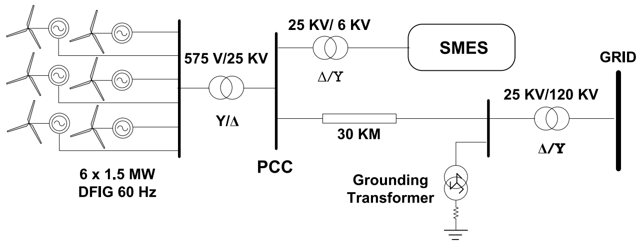

FIGURE 1. System under study.

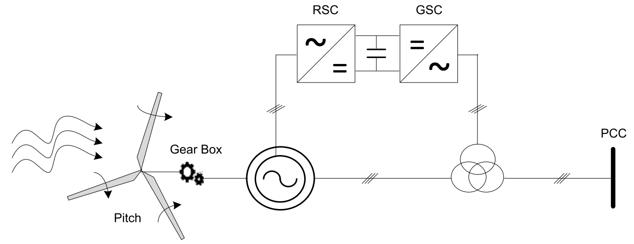

FIGURE 2. A typical model of doubly fed induction generator.

TABLE 1. Parameters of the system under study.

Parameters of DFIG	
Rated Power	9 MW
Stator Voltage	575 V
Frequency	60 Hz
Stator Resistance R_s	0.023 pu
Rotor Resistance R_r	0.016 pu
Converter Rated Voltage	1000 V
V_{pcc} Based Value	25 kV
Parameters of TL (Positive and Zero Sequence)	
R_1, R_0(Ω/Km)	0.1153 Ω/Km, 0.413 Ω/Km
L_1, L_0 (H/Km)	1.05 x 10^{-3} H/Km, 3.32 x 10^{-3} H/Km
C_1, C_0 (F/Km)	11.33 x 10^{-9} F/Km, 5.01 x 10^{-9} F/Km
Grid data	
Grid Capacity	2500 MVA
Grid Voltage	120 kV
X_0/X_1	3
Parameters of SMES Unit	
Rated Energy	3 MJ
Coil Inductance L_{SM}	1.5 H
Rated Current I_{SM}	2 kA
DC Link Capacitance ($C_{DC-LINK}$)	18 mF

the SMES coil with the system. Detailed explanation of the proposed control scheme is provided in section II-B.

II. SYSTEM UNDERSTUDY

The system under study comprises six identical 1.5-MW DFIGs connected to the grid through two step-up transformers and 30 km distribution line as shown in Fig. 1. The proposed SMES unit is connected to the PCC via a coupling transformer. The data of the investigated system that is simulated using Matlab/Simulink software are listed in Table 1. Main components of the studied system are briefly elaborated below.

A. DOUBLY FED INDUCTION GENERATOR

DFIG has dominated the WECS installations since 2006 [1] and it contributed about 50% of the wind market shares [30].

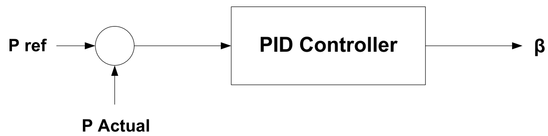

FIGURE 3. A typical generic model of a conventional pitch control.

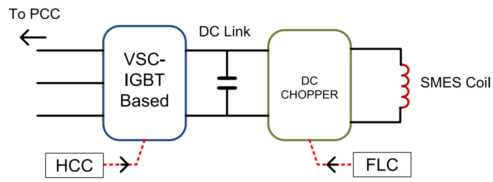

FIGURE 4. SMES unit configuration.

DFIG popularity is gained due to its capability to capture more wind energy and the partial capacity of the interfacing converters when compared with other WECS types. A typical model of a DFIG is shown in Fig. 2.

As mentioned above, pitch control is used to adjust the rotational angle of the turbine blades to nearly constant value when it encounters wind speed variation. The pitch control system used since the early-stage design of DFIGs is based on proportion-integral-derivative (PID) conventional controller due to its low cost and simple design [31]. The pitch angle β is dictated by the PID controller when it is energized by the error signal of the reference output power and the measured power as shown in Fig. 3 and (1) below. The most challenging task of this conventional controller is the accurate tuning of the PID parameters to fit the best response of the blades position [32].

$$\beta = \mathrm{K_P}[\mathrm{e_p}\,(\mathrm{t}) + \frac{1}{T_i}\int_0^{\mathrm{t}} \mathrm{e_P}\,(\mathrm{t})\mathrm{dt} + \mathrm{T_i}\frac{\mathrm{de_P}}{\mathrm{dt}}] \tag{1}$$

where: $K_i = \frac{K_p}{T_i}$; $K_d = \frac{K_p}{T_d}$ and $e_p = P_{ref} - P_{actual}$ K_p, K_i, and K_d are the gains parameters of the PID Controller.

B. SUPERCONDUCTING MAGNETIC ENERGY STORAGE UNIT

The SMES unit configuration adopted in this paper is as shown in Fig. 4. The SMES control algorithm presented by the same Authors in [33] is adopted in this paper with some modifications to the PIs parameters, FLC rules and HCC.

As shown in Fig. 4, a high temperature-based superconductor is interfaced with the PCC through a VSC and DC-DC

TABLE 2. Parameters of PI controller.

PI → $I_{d\text{-}Ref}$	$K_P = 1$	$K_I = 3$
PI → $I_{q\text{-}Ref}$	$K_P = 0.5$	$K_I = 6$

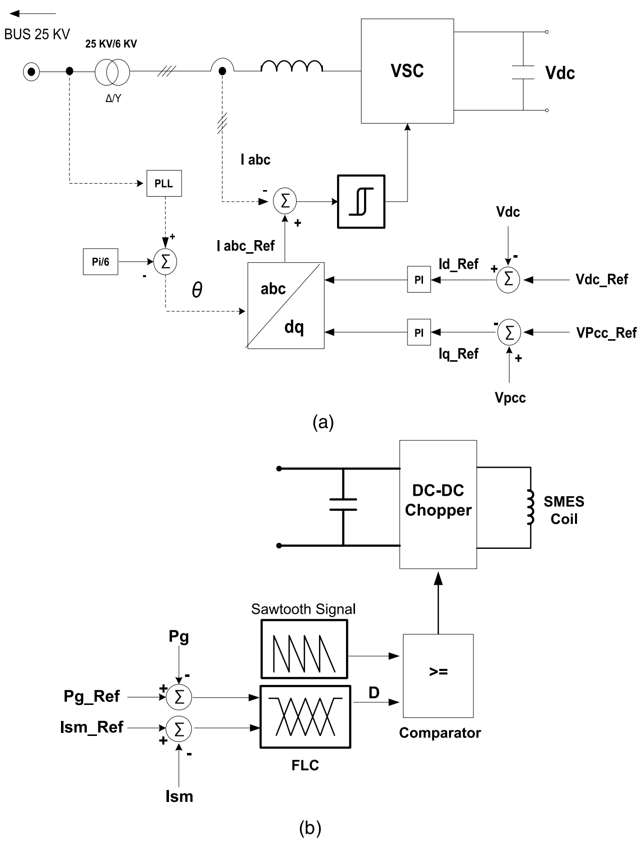

FIGURE 5. SMES unit control algorithm; (a) VSC control, (b) FLC.

TABLE 3. Fuzzy rules for duty cycle of DC-DC chopper.

ΔPG / ΔISM	VS	S	B	VB
VS	SBY	S	MS	VS
S	B	S	MS	VS
B	MB	S	S	MS
VB	VB	SBY	SBY	SBY

TABLE 4. Rules of duty cycle.

Duty Cycle (D)	SMES coil mode
$0 \le D < 0.5$	discharging
$D = 0.5$	standby
$0.5 < D \le 1$	charging

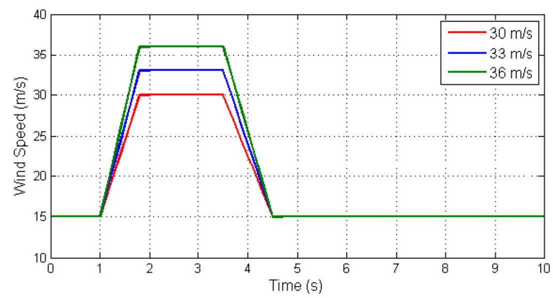

FIGURE 6. Applied wind gust profiles.

chopper to facilitate the energy exchange between the coil and the PCC by controlling their insulated gate bipolar transistor (IGBT) switches. The VSC and the chopper are linked with a DC-link capacitor to enable optimal energy transfer between the coil and the grid by maintaining the DC-link voltage at a constant level. The VSC is controlled by hysteresis current controller while the DC-DC chopper is controlled by fuzzy logic controller. The control parameters used in the investigated case study are presented in Tables 2 and 3. The detailed FLC and HCC as shown in Fig. 5 can be found in [33], [34] and are briefly explained below.

To avoid large oscillation that may be caused by the HCC, the inductor is connected before the VSC as shown in Fig. 5(a). The HCC employs the error in the 3-phase currents at the PCC, $I_{abc\_ref} - I_{abc}$ where I_{abc_ref} is obtained from the dq-abc transformation. The d-q reference frame is dictated by I_d and I_q which are respectively obtained from the voltage error signals at the DC-link ($V_{dc\_ref} - V_{dc}$) and at the PCC ($V_{pcc\_ref} - V_{pcc}$). For optimum energy transfer between the SMES unit and the system, the fuzzy rules are set up based on the SMES coil current I_{sm} and the DFIG power P_g to generate the duty cycle signal D for the DC-DC chopper as shown in Fig. 5(b).The membership functions of these inputs are provided in Table 3. For power and current error signals, ΔP_g and ΔI_{sm}, the membership functions applied are VS=Very Small; S-Small; B-Big; and VB=Very Big. On the other hand, the membership functions of the duty cycle as the output of the FLC are SBY=Standby; S=Small; MS=Medium Small; VS=Very Small; B=Big; MB=Medium Big; and VB=Very Big. The duty cycle working rules is setup based on Table 4.

III. RESULTS AND DISCUSSION

The simulated DFIG model is designed to provide 9 MW power at an average wind speed of 15 m/s. To investigate the detrimental impacts of wind gust of short durations on the DFIG LVRT capability, extreme wind gust profiles of 30 m/s, 33 m/s, 36 m/s as shown in Fig. 6 are applied to the studied system. All wind gust profiles are assumed to start at t=1.0s and ends at 4.5s after which the wind speed retains its constant average value of 15 m/s. These profiles are extracted from the Meteoalarm averaged data recorded in [8].

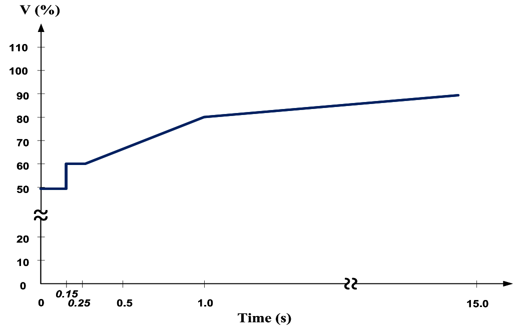

FIGURE 7. Low voltage ride through limit of Spain.

A. COMPLIANCE WITH LVRT OF SPAIN

The DFIG LVRT capability is investigated during the above-mentioned wind gust events. Fault ride through codes have been established by the transmission line operators to maintain the connection of the wind turbine during disturbance events. One of the strictest LVRT codes is set in Spain as shown in Fig. 8. In this code, the minimum allowable voltage drop at the PCC is 50% of the nominal rated voltage that is last for 1.5s. After fault clearance, voltage profile must be recovered to 60% of the nominal value and lasts for 0.25s then gradually increase to 80% in a 1.0s after which it increases gradually to 90% of the nominal voltage. When this code is violated due to any fault or disturbance event, the wind turbine generator must be disconnected from the grid.

The effect of such wind gusts on the voltage profile at the PCC is shown in Fig. 8 without and with the proposed SMES controller. Results in Fig. 8 show that prior to wind gust, the voltage at the PCC is maintained at 1 pu. Without the connection of the SMES unit, the PCC voltage profile drops and fluctuates within the entire duration of the wind gust. After the period of wind gust, the settling time taken by the voltage profile to retain its nominal level is substantial. This voltage drop reaches 0.3pu when a wind gust of 30 m/s hits the wind turbines. When the SMES unit with the proposed controller is connected, the voltage drop is significantly reduced as shown in Fig. 8(a). When the wind gust level is increased to 33 m/s, the voltage drop at the PCC increases to reach 0.4 pu without the SMES unit which is mitigated with the connection of the SMES unit to just 0.1 pu as can be seen in Fig. 8(b). In this case, without the SMES unit, voltage fluctuates and tends to hit the LVRT limit of Spain as shown in the inserted-zoomed area in Fig 8(c). If the protection system is quite sensitive, the small violation of the LVRT limit will activate the protection system and disconnect the wind turbine from the grid. When a wind gust of 36 m/s hits the turbine blades and without the SMES unit, a rapid fluctuation in the voltage profile at PCC is observed and the voltage level drops to about 0.5 pu and violates the LVRT limit of Spain. In this case, the wind turbine must be disconnected from the grid, however, when the proposed SMES unit is connected, the voltage profile is regulated to a level well above the LVRT threshold limit of Spain. The mechanical pitch during this short period should be back to its default

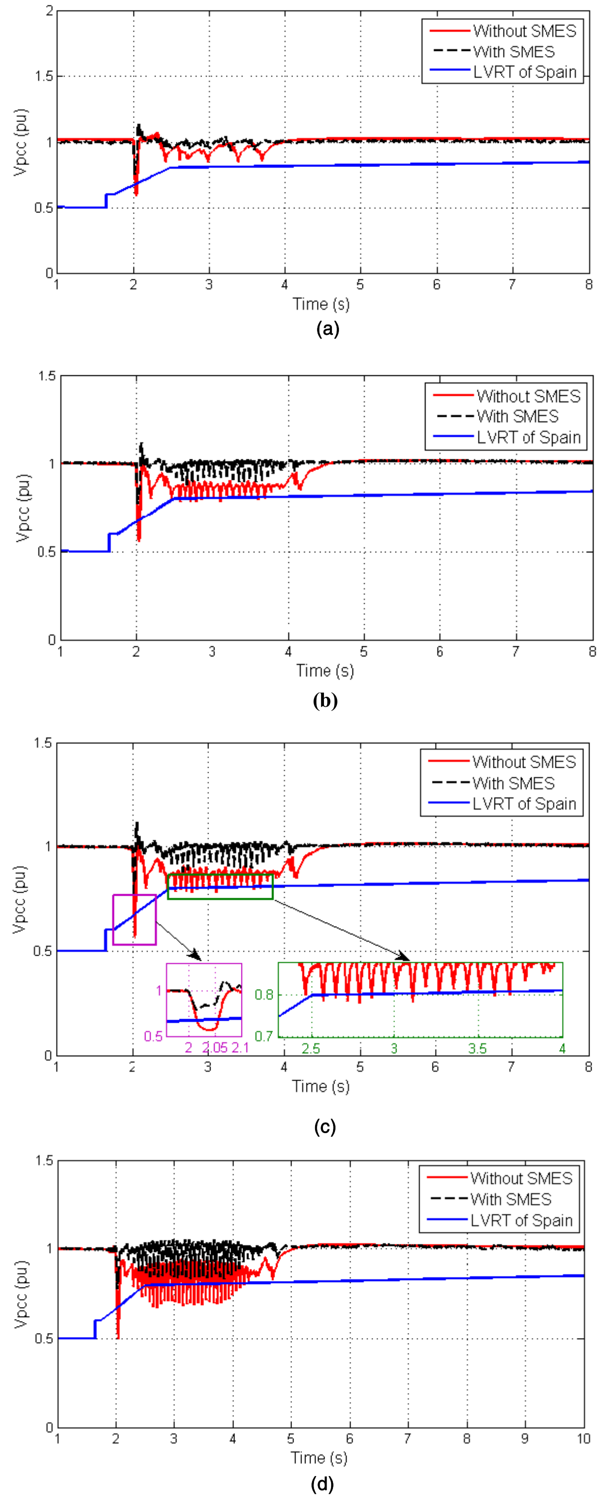

FIGURE 8. Voltage profile at the PCC with and without SMES unit; (a) Wind gust 30 m/s, (b) Wind gust 33 m/s, (c) Inserted-Zoomed for wind gust 33 m/s, and (d) Wind gust 36 m/s.

blade position however, for such rapid change in the wind speed, the mechanical repositioning of the blades cannot be achieved and external support of the SMES unit is necessary to maintain system reliability. For all cases, following the wind gusts shown in Fig. 6, the higher the wind speed the

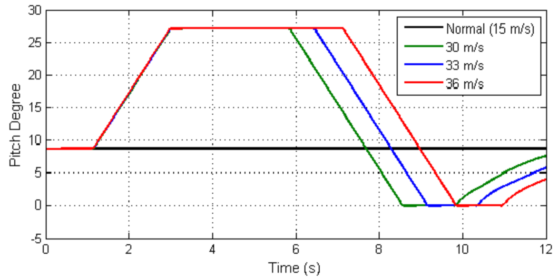

FIGURE 9. Pitch control response during various levels of wind gusts.

more rapid oscillation can be observed. This phenomenon may be attributed to the fact that high wind speed is reaching the maximum speed limit of the pitch controller rapidly while the sensors measurement and the pitch mechanism system is much slower.

Fig. 9 shows the pitch control response for the investigated wind gust profiles. For a nominal wind speed of 15 m/s, the blade pitch is designed at a default angle of 9 degrees to match the nominal generator speed. However, for all wind gust scenarios, the pitch angle of the turbine blades is automatically adjusted to 27.5 degrees and attempts to retain its default position after the wind gust duration. Large wind gust levels result in increasing the settling time of the turbine blades to retain its default position. It can be also seen that the mechanical pitch angle control response is very slow as it start to function at t=3s and it could not adapt the blades for such high wind speed with short duration. After the wind gust event and when the wind speed settles back to15 m/s at 4.5 s, the blades retain its default position at t=12 s.

The generated power of the DFIG (P) is shown in Fig. 10. When a 30 m/s wind gust hits the turbines blades (Fig. 10(a)) and without the SMES unit, the generated power experiences significant oscillations that reaches almost 3.0 pu. However, when the SMES unit with the proposed controller is connected, such oscillations can be reduced significantly and reach a steady-state level faster. For the cases of 33 m/s and 36 m/s wind gusts shown in Figs. 10(b) and (c) respectively, power fluctuation is becoming more aggressive particularly for the case of 36 m/s with significant maximum overshooting. Oscillation, maximum overshooting and settling time of the dispatched power are significantly reduced when the SMES unit is connected.

The profile of the energy transferred between the SMES coil and the PCC during the wind gust events is shown in Fig. 11. It can be seen that, SMES coil energy tends to absorb some amount of the excess power generated due to the high wind speed; the higher the wind speed, the larger the energy transfer to the coil. It is to be observed that the energy exchange between the SMES coil and the PCC is based on the control input parameters, P and I_{sm}. Therefore, following the power increment at the PCC due to wind gust, SMES coil tends to absorb the surplus power but it should be noted that the recovery time after the wind gust event is less due to the response of the pitch mechanism.

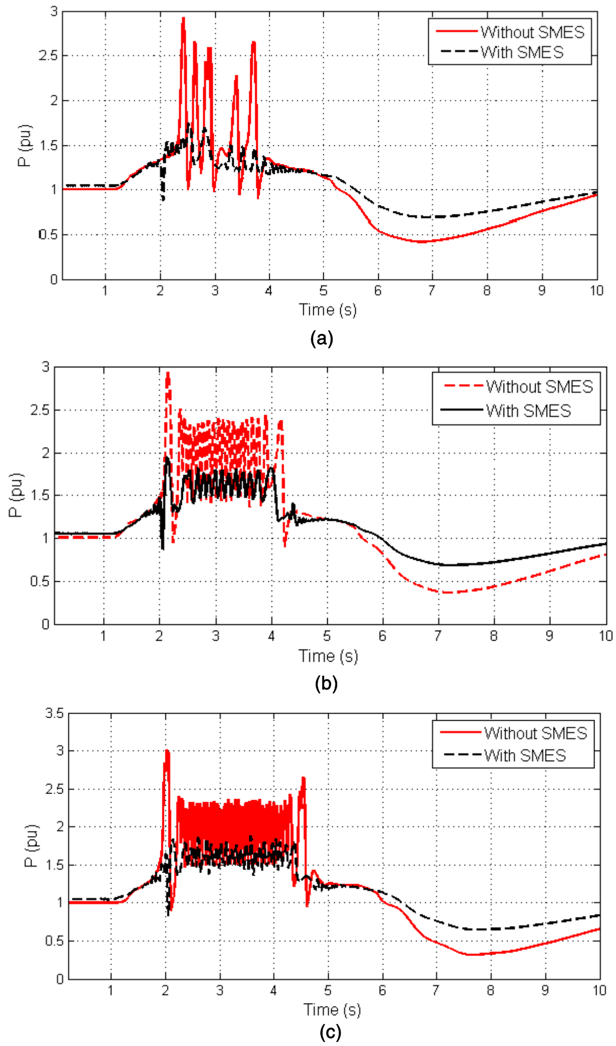

FIGURE 10. DFIG power at the PCC with and without SMES unit for; (a) Wind gust 30 m/s, (b) wind gust 33 m/s, and (c) wind gust 36 m/s.

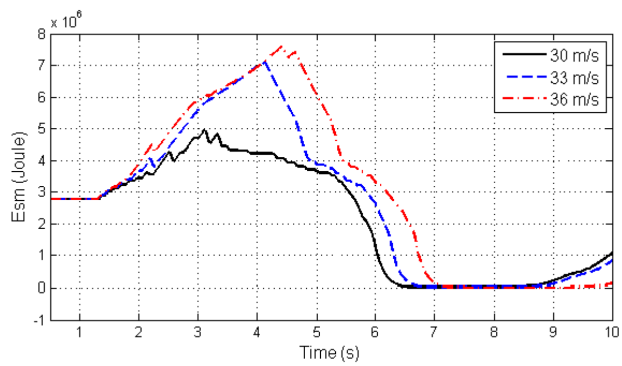

FIGURE 11. Energy transfer between the SMES coil and the PCC.

IV. CONCLUSION

An investigation on the impacts of short extreme wind gusts on the LVRT of a DFIG grid-connected turbine is presented. Simulation results indicate that the slow response of the pitch control mechanism cannot adapt the blades positions during wind gust events. This calls for external supports to enable the DFIG complying with the grid codes developed by the transmission line operators in various countries. The proposed SMES controller in this paper can effectively regulate the voltage profile at the PCC during wind gusts. Results show that, with the proposed SMES unit, the voltage profile at the PCC will comply with the Spain LVRT during wind gusts whereas, the wind turbine generator should be disconnected without the connection of the SMES unit to the system for all studied scenarios. Furthermore, the results show that the significant oscillations in the DFIG power can be significantly reduced when the proposed SMES controller is employed.

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