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Alleviation of Extremely Power and Voltage Variations Caused by Wind Power and Load Demand Using SMES

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Abstract

Due to the high variations in wind speed and the continuing changes in load power demand (LPD), power and voltage at the point of common coupling (PCC) fluctuate according to the variations of injected wind power generation (WPG) and LPD simultaneously. Superconducting magnetic energy storage (SMES) plays a significant role in alleviating the power/voltage at PCC. This paper shows the impact of SMES in enhancing the performance of interconnected WPG system during high wind gust variations and the changes in LPD. WPG includes squirrel-cage induction generator (SCIG) type with a shunt-connected capacitor for improving the power factor. WPG, SMES and the load are located at PCC. Fuzzy logic control (FLC) is used with the DC-DC chopper to control the power exchange between AC system and SMES. FLC is designed where SMES can absorb/inject real power from/to the grid. On the other hand, reactive power is controlled to adjust the variation of PCC voltage. Two inputs are applied to the FLC; the summation of wind power variation and change of LPD as the first input and the variation of SMES current is the second one to control active power transferred between SMES and AC system. The suggested control approach of SMES is a fast response, as it successfully controlled the PCC voltage, line active and reactive powers during wind gusts and the variations of the load side.

Keywords

fuzzy logic control, load power demand, superconducting magnetic energy storage, wind gust, wind power generation

1 Introduction

Nowadays, renewable energies are becoming one of the most important energy resources used in both of transmission and distribution networks to aid the conventional energy resources in supplying the several types of residential, commercial, and industrial loads [1, 2]. The use of renewable energy sources is one of the important strategies used to reduce the dependence on fossil fuels and consequently, mitigating the climate change impacts. Wind and solar energies are considered the most important renewable energy resources which have grown rapidly in all countries due to the large shortage in the conventional energy resources and the rising of the price of the fossil energies around the world. However, the main drawback of the photovoltaic (PV) and wind systems is that generation power outputs depend on climatic conditions such as wind speed, solar irradiance, and temperature. Therefore, the stability of the electrical power system will be affected by these conditions [3].

On the other hand, energy storage systems (ESSs) are widely used in power grids. The main contribution of employing energy storages in electrical power networks is to mitigate the active/reactive power transfer from/to the grid during normal conditions and when it is subject to disturbances. Energy storage technologies can charge/discharge the electrical power from/to the grid during the power transfer between distributed generation (DG) systems and the grid side [4, 5]. Energy storage technologies can play a very important role in DG systems. These technologies work as a very fast pulsating power supply which can improve the power exchange between DGs and grid side in steady-state and abnormal operations [6, 7]. Some studies have been conducted to utilizing the PV or wind generation by connecting them to the grid directly without storage unit [8, 9]. However, the storage device is considered an important part of the system as it improves the quality and reliability of the output power.

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Superconducting magnetic energy storage (SMES) is one of the very significant energy storage technologies in the application of PV and wind generation systems. Due to the intermittent nature of the renewable energy sources, the output power of DGs will fluctuate. These fluctuations can be mitigated by using SMES for absorbing/injecting energy from/to the grid [10]. The main advantage of SMES during the charging/discharging process is the fast response. In addition, it has a longer life time and higher efficiency compared to the other energy storage types [11].

Several studies demonstrated the behavior of SMES with WPG. The impact of SMES in improving the transient stability in the existence of doubly fed induction generator (DFIG) type is presented in [12, 13]. The application of SMES to regulate the fluctuation of PCC voltage as well as real/reactive power transmitted between the utility grid and the WGP systems during extreme wind gust by using SMES is reported in [14]. The SMES impact for minimizing the voltage fluctuations of the unbalanced three-phase radial distribution system connected to WPG system with high power penetration level during wind speed gusts is presented in [15]. Authors in [16, 17] have evaluated and highlighted the improvement of voltage sag and swell events of the distribution networks interconnected with DFIG and SCIG wind generation by installing the SMES unit. SMES can control the output power of wind farms at normal wind speeds [18], it also used for improving the output power of WPG at the slow and small power fluctuation events [19]. Nevertheless, the mitigation of WPG output power during high wind gusts and taking into consideration the load power variations have not addressed in the literature. In addition, the regulation of PCC voltage by injecting/absorbing reactive and active power between SMES and PCC bus in the presence impact of load power variations have not been highlighted as well. Therefore, the above two mentioned points are considered the main emphasis of this paper.

In this work, an improved control strategy is applied to a SMES system to improve and mitigate the fluctuations of both active and reactive powers which transfer between the utility grid and WPG system. Also, the PCC bus voltage variation during the highly changes of wind speed as well as the load power. FLC's inputs take into consideration the variations of the load power side in additional to the changes due to wind speed variation. By installing SMES, PCC bus voltage is regulated to the acceptable value (1.0 pu), SMES could also mitigate the variation of the real and reactive power transfer between the WPG and the grid although the extreme change in wind speed and the random variations in the load power. In short, the main contributions for this work can be summarized as follow:

- Mitigating the extreme variations of line real and reactive powers caused by wind gust and changes of load power.
- Improving the fluctuations of the PCC voltage to the suitable value due to the variation of wind speed.
- Compensating both active and reactive powers which transfer through transmission line as well as the reactive power which required for the excitation of SCIG wind turbine during steady state and transiently events.

The outline of this paper is offered as follows. Section 2 illustrates the main problem which investigates in this paper. Section 3 describes the modeling of the studied system and wind turbine. The complete model of SMES and the proposed FLC method is presented in Section 4. Section 5 describes the complete simulation results. Comprehensive conclusions are highlighted in Section 6.

2 Problem description

The natural variations of the wind speed caused fluctuations in the injected wind power to the grid as well as the bus voltage of the interconnected bus, therefore the line real and reactive powers are changing according to the shape of wind speed variations. Also, the random fluctuations in the load power present a bad response to real/reactive power transfer between WPG and AC grid, as well as the voltage profile of the PCC bus. Therefore, the energy storage system (EES) plays a vital role to mitigate the line real/reactive power and the PCC bus voltage during the variations of both wind speed and the load power. SMES is considered one of the important energy storage techniques, which preferred when using wind farm applications. SMES can charge/discharge rapidly to face the abnormal conditions in the system. FLC is utilized to control the duty cycle (D) of the two-quadrant DC-DC chopper to operate with fastly charging/discharging modes to alleviate the line real/reactive power and the PCC bus voltage as well.

3 Modeling of the test system

3.1 Wind turbine model

The wind turbine mechanical power is expressed mainly as a function of the power coefficient (C_p) and the cubic wind speed (υ) in Eq. (1) [20].

$$P_m = 0.5C_P(\beta,\lambda)A\rho\upsilon^3, \tag{1}$$

where P_m, β, A, λ, and ρ are the turbine mechanical power, blade pitch angle, turbine swept area, the rotor tip speed ratio, and the air density, respectively. C_p can be determined with the blade pitch angle and the tip speed ratio [21]. The mechanical characteristics of the wind turbine model are clarified in Eq. (2) [22, 23], all values of coefficients C_1 to C_6 are reported in [23].

SCIG is typically demonstrated as a traditional PQ bus, with the real power generated and reactive power demand specified. However, the reactive power demand can be stated as a function of the bus voltage in Eq. (3), if the SCIG is modeled as an improved PQ bus by using the demonstration introduced in [24] and later used in [25], the complete equivalent circuit of SCIG is shown in Fig. 1.

$$\begin{aligned} C_P(\beta,\lambda) &= C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{-\frac{C_5}{\lambda_i}} + C_6\lambda_i \\ \frac{1}{\lambda_i} &= C_1\left(\frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}\right), \end{aligned} \tag{2}$$

$$Q_G = V_s^2\left(\frac{X_c - X_m}{X_m X_C}\right) + \frac{X}{V_s^2}P_G^2, \tag{3}$$

where Q_G is the excitation reactive power of the generator, P_G is the active power generation, X_c is the compensation capacitive reactance which unitized to improve the power factor, X is the summation of rotor X_r and stator X_s reactances, R_s is the stator resistance, R_r is the rotor resistance, and X_m is the magnetizing reactance as shown in Fig. 1. The rotor voltage of the SCIG based wind turbine is equal to zero, therefore, the voltage equations of the machine can be expressed as follow [26]:

$$\begin{aligned} v_{ds} &= -R_s i_{ds} + \omega_s\left(\left(L_{s\sigma}+L_m\right)i_{qs} + L_m i_{qr}\right) \\ v_{qs} &= -R_s i_{qs} - \omega_s\left(\left(L_{s\sigma}+L_m\right)i_{ds} + L_m i_{dr}\right) \\ 0 &= -R_r i_{dr} - s\omega_s\left(\left(L_{r\sigma}+L_m\right)i_{qr} + L_m i_{qs}\right) \\ 0 &= -R_r i_{qr} - s\omega_s\left(\left(L_{r\sigma}+L_m\right)i_{dr} + L_m i_{ds}\right), \end{aligned} \tag{4}$$

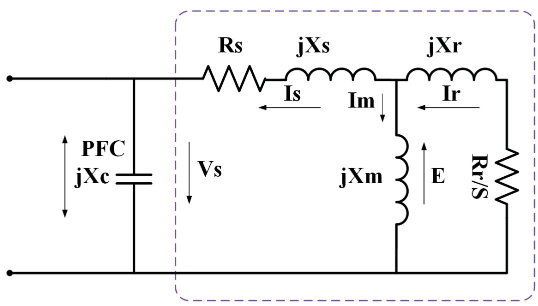

Fig. 1 Equivalent circuit of SCIG

where $L_{s\sigma}$, $L_{r\sigma}$, i_{ds}, i_{qs}, i_{dr}, i_{qr}, v_{ds}, v_{qs} are the stator leakage inductance, rotor leakage inductance, stator direct, quadrature current, rotor direct, quadrature current, stator direct, and quadrature voltage, respectively. The active power generation (P_G) and the compensation reactive power (Q_G), are discussed in Eqs. (5) and (6) [26]:

$$P_G = v_{ds}i_{ds} + v_{qs}i_{qs}, \tag{5}$$

$$Q_G = v_{qs}i_{ds} - v_{ds}i_{qs}. \tag{6}$$

3.2 Power system model

As shown in Fig. 2, the complete power system model which used as a case study in this paper. The studied system is a wind farm containing six identical wind turbines with 1.5 MW each. These units are connected to a 25-kV distribution system that supplies the power to a 120-kV grid through a 30 km, 25-kV transmission line. The stator winding of SCIG wind turbines is connected directly to the PCC bus and their rotor is driven by a fixed-pitch angle wind turbine. The capacitor bank at each wind turbine low voltage bus compensates the SCIGs with the initial required reactive power. The rating of SMES is 4.5 MJ/1.25 kWh and a large load is connected at PCC bus. The complete system is performed in MATLAB/Simulink® and simpower system package.

4 The proposed FLC method and SMES model

4.1 Modeling of SMES

SMES model used in this work is shown in Fig. 3. It consists of a Wye-Delta (25 kV/1.2 kV) transformer, pulse width modulator (PWM), voltage source converter (VSC) using an insulated-gate bipolar transistor (IGBT), DC link capacitor, two-quadrant DC-DC chopper using IGBT, and large inductance as a superconducting coil. The VSC involves two IGBT bridges to decrease the harmonics. VSC and the DC-DC chopper are connected by a DC

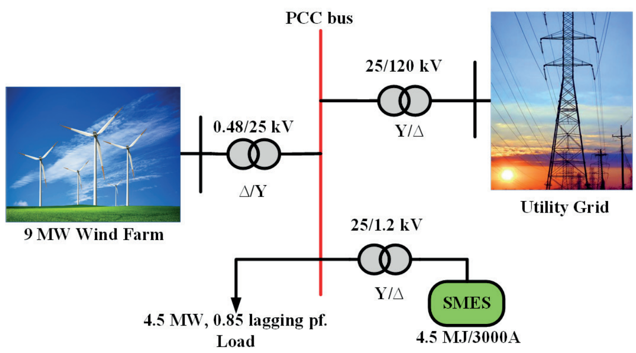

Fig. 2 Power system model under study

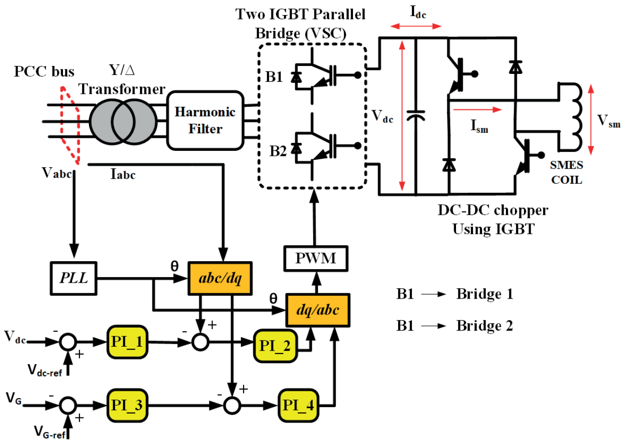

Fig. 3 Schematic diagram of VSC control SMES system

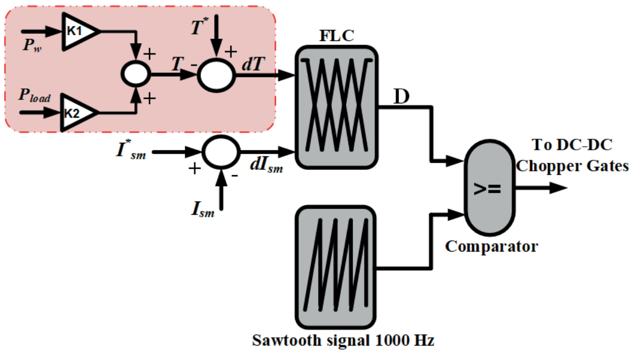

Fig. 4 FLC system for the chopper circuit

link capacitor. VSC provides a power electronic interface between the PCC bus and the SMES coil, also it operates as a voltage regulation mode to mitigate the PCC voltage during the periods of variation. Phase-locked loop (PLL) technique is used to maintain the converter switching at a fixed prearranged frequency level [27]. DC link voltage, V_{dc} and grid point voltage, V_G are sustained constant by the VSC. The control system of the VSC is displayed in Fig. 3. The SMES stored energy in Joules and the charging/discharging SMES power in Watts can be illustrated in Eqs. (7) and (8), as follows:

$$E_{sm} = \frac{1}{2} L_{sm} I_{sm}^2, \tag{7}$$

$$P_{sm} = \frac{dE_{sm}}{dt} = I_{sm} V_{sm}, \tag{8}$$

where L_{sm}, I_{sm}, V_{sm} are the inductance of SMES coil (H), SMES coil current, and the average value of SMES coil voltage, respectively. Tables 1 to 4 show SGIG parameters, SMES unit parameters, the main rules of the duty cycle (D), and the parameters of PI controllers for VSC and weighting factors of FLC, respectively.

4.2 Proposed FLC Method for the chopper circuit

For controlling the active power transmitted between the PCC bus and SMES coil, DC-DC chopper circuit is utilized with the proposed FLC to control its duty cycle (D), this is discussed in Fig. 4. The proposed control takes into consideration the difference between wind power and load power (T), then it compares with the reference value. This means the load is approximately locally fed from wind power and SMES without using power from the utility grid and reducing the line real/reactive power variations due to wind gust and randomly load power.

Table 1 SGIG parameters [14]

Element	**Value**
Power rating	1.5/0.9 (MVA)
Voltage	480 (V)
Magnetizing reactance	1.354 (pu)
Stator resistance	0.01965 (pu)
Stator reactance	0.0397 (pu)
Rotor resistance	0.01909 (pu)
Rotor reactance	0.0397 (pu)

Table 2 Parameters of the SMES

Element	Value
Rated SMES energy (E_{sm})	4.50 MJ
SMES inductance (L_{sm})	1.0 H
SMES current (I_{sm})	3 kA
DC capacitor	10 mF

Table 3 Duty cycle (D) rules

Value	SMES mode of operation
D = 0.5	Standby condition
$0 \leq D < 0.5$	Discharge condition
$0.5 < D \leq 1$	Charge condition

Table 4 PI controllers' parameters for VSC and weighting factors of FLC

	PI_1	PI_2	PI_3	PI_4	K1	K2
K_p	0.001	0.8	0.55	0.8	0.1	-0.3
K_i	0.15	200	2500	200		

There are many benefits of using fuzzy logic controllers compared with the conventional controllers [28], as follows; (i) Compared to conventional Proportional - Integral - Derivative (PID) controllers, FLCs are more robust since they can cover a much wider range of operating conditions than PID. FLC can operate with noise and disturbance of different nature. (ii) Developing a FLC is cheaper than developing a model-based or other controller for the same thing. (iii) Since it is easier to understand and modify their rules, FLCs are customizable which not only use a human operator's strategy but also are expressed in natural linguistic terms. (iv) It is attractive because it easy to learn how FLC operate and how to design and apply them to a concrete application.

The main four processes of FLC is shown in Fig. 6 (e), where Fuzzification module is the functions of which are first, to read, measure, and scale the control variable (speed, acceleration) and, second, to transform the measured numerical values to the corresponding linguistic (fuzzy variables with appropriate membership values), *Knowledge base* includes the definitions of the fuzzy membership functions defined for each control variables and the necessary rules that specify the control goals using linguistic variables, *Inference engine* should be capable of simulating human decision making and influencing the control actions based on fuzzy logic, and *Defuzzification module* converts the inferred decision from the linguistic variables back the numerical values.

FLC is designed as two inputs and one output, wherein, the variation in SMES current (dI_{sm}) is considered an input, the second input is the summation of wind power (P_w) and load demand variations (dT). The duty cycle (D) is the output variable of FLC. The relation between V_{sm} and V_{dc} can be expressed as Eqs. (9) and (10) [29]:

$$V_{sm} = (1-2D)V_{DC}, \tag{9}$$

$$I_{DC} = (1-2D)I_{sm}, \tag{10}$$

where I_{dc} is the direct current flow between the chopper circuit and VSC and V_{dc} is the DC-linked capacitor voltage.

SMES coil charges, discharges, and operates in standby mode of operations by using the proposed FLC of the chopper circuit, as offered in Fig. 5. FLC of the chopper circuit can effectively control voltage of the SMES coil negatively (during IGBT switched off) or positively (during IGBT switched on), this, in turn, the SMES stored energy can be discharged/charged, respectively. Consequently, the SMES coil (SC) can be charged or discharged according to the average value of SC voltage positive or negative value, which is determined by the duty cycle value of the proposed FLC of chopper circuit. In case of the duty cycle is equal to 0.5, then SMES unit is activated in a stand-by mode of operation, but when it is larger than 0.5 or less than 0.5, the SMES stored energy is either charged or discharged, respectively.

The model of FLC is implemented with the graphical user interface (GUI) which running with MATLAB program. Gaussmf-type membership function (MF) is used in fuzzifying both inputs and output with five sets on 0–1 scale for the MF degree. The standard Gaussian-curve equation is stated in Eq. (11) [30]:

$$f(x,\sigma,c) = e^{-\frac{(x-c)^2}{2\sigma^2}}, \tag{11}$$

where c is the parameter that decides the center of the peak, σ is the width of the bell curve. Center of gravity, which is a widely used method in fuzzy models, is used for defuzzification process where the expected output (z_o) can obtain by Eq. (12) [31]:

$$z_o = \frac{\int z.\mu_c(dz)}{\int \mu_c(dz)}. \tag{12}$$

The SMES current and the summation of wind power and the load power variations as well as the corresponding duty cycle are arranged with the logical linguistic of (IF-AND–THEN) routines to determine the rules of fuzzy interface system (FIS), then the output numerical values can be calculated as an output of the defuzzification process, as shown in Fig. 6.

5 Results and discussions

The main impact of SMES in the presence of extreme wind gust and variable loads connected to PCC bus as shown in Fig. 2, is analyzed. Fig. 7 presents the wind gust variation, the profile of variable load demand (i.e. 4.5 MW, 0.85 lagging power factor) which connected at PCC bus is shown in Fig. 8. WPG, SMES, and the load are connected at the PCC bus. The SCIG is compensated with the appropriate reactive power with capacitor which interconnected at each low bus voltage. FLC is proposed for operating the chopper circuit, the SMES is operated initially with the full charge energy (4.5 MJ), and the initial current is 3 kA.

Fig. 9 presents the voltage profile of PCC during high variation of both wind and load with/without installing SMES. PCC bus voltage is decreased to less than 0.95 pu due to the load variations then also, it is dropped to 0.85

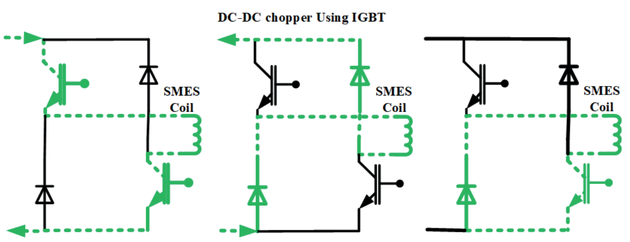

Fig. 5 Operation modes of the DC–DC chopper. (a) Charging mode, (b) Discharging mode, (c) Standby mode.

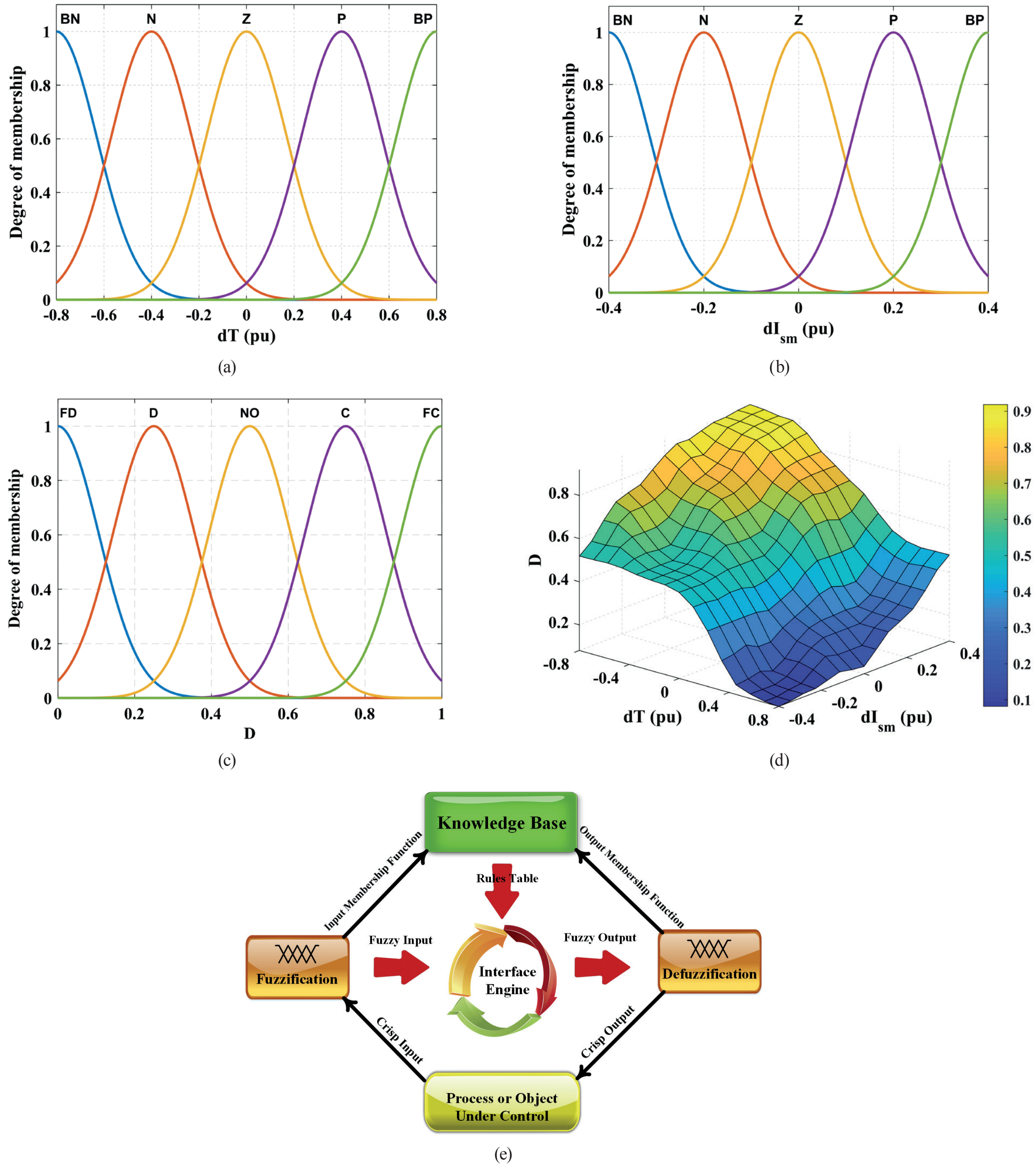

Fig. 6 Inputs and output variables of membership functions and FLC complete process. (a) Input 1 of MF, dT (pu), (b) Input 2 of MF, dIsm (pu), (c) The output of MF, (D), (d) The 3-D graph for inputs-output MFs, (e) Complete procedure of FLC. BP = Big positive, P = Positive, Z = Zero, N = Negative, BN = Big Negative, FC = Fast charging, C = Charging, NO = No action, D = Discharging, FD = Fast discharging.

pu due to the wind gust, without using SMES. The proposed FLC control of the SMES could rapidly discharge/charge active power between SMES and AC system to minimize the fluctuation due to variations of the load and the random wind power as well.

Furthermore, the SMES reactive power can be generated/absorbed to achieve the best improvement of the voltage profile of the PCC bus. Therefore, the real and reactive powers are injected/released in order to regulate the PCC voltage at 1.0 pu during the extreme wind speed and load fluctuations. It is clear from Fig. 9, by using SMES, the PCC bus voltage is regulated to 1.0 pu.

Fig. 10 shows the behavior of active and reactive power at PCC bus. The real power at PCC bus dropped sharply

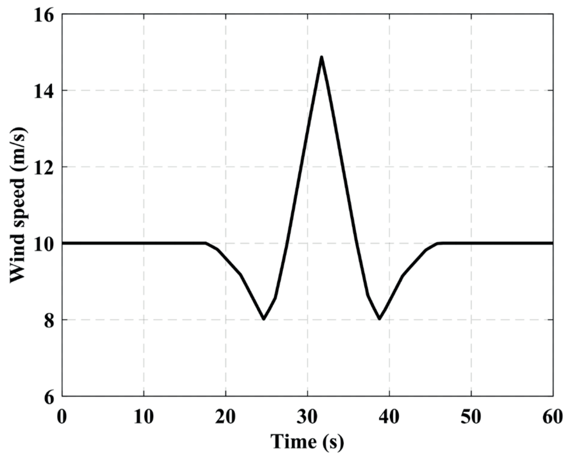

Fig. 7 Response of wind gust speed variations

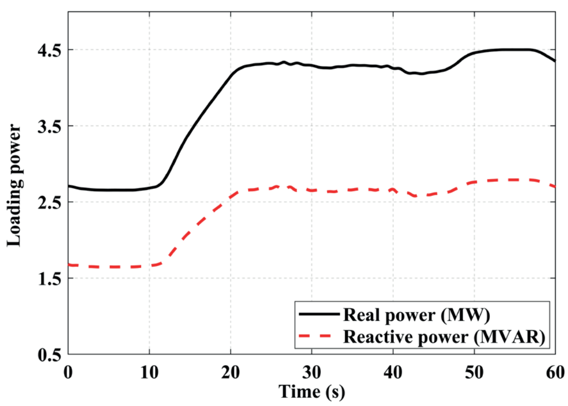

Fig. 8 Response of the load demand variations

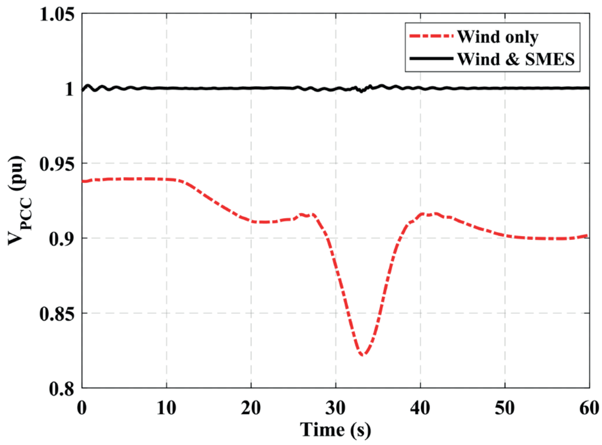

Fig. 9 Response of PCC bus voltage

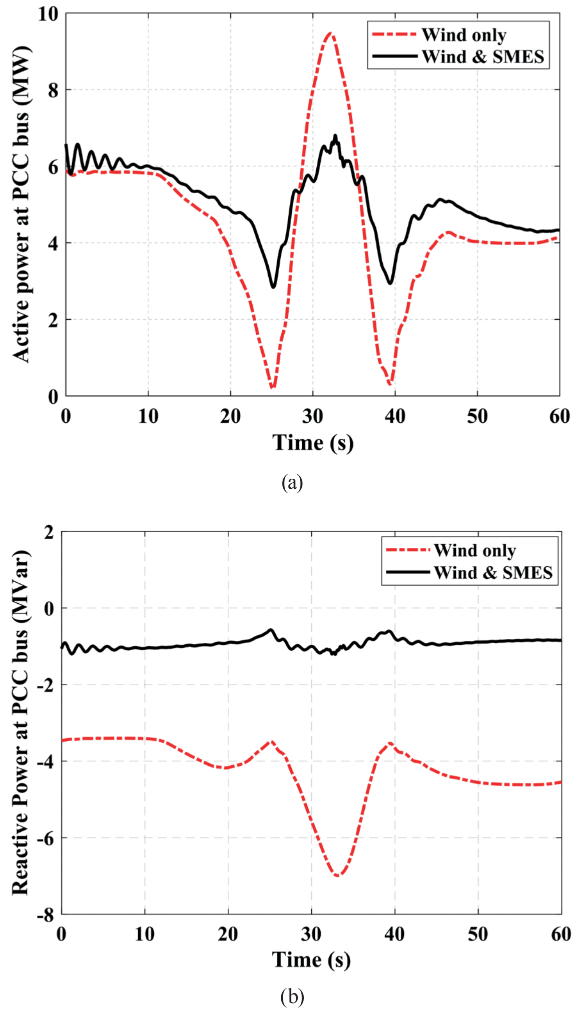

Fig. 10 Response of line active and reactive powers at PCC bus. (a) Active power at PCC bus, (b) Reactive power at PCC.

to zero power approximately due to the wind speed, then returns to increase dramatically to 10 MW without SMES. However, the response of the power variation is improved by using SMES. With installing SMES, the real power absorbed/injected at the PCC bus during low/high wind speed events is relieved. The limits of the fluctuated real power which transfer between the PCC bus and wind farm are 9.462 MW and 0.342 MW without SMES, these limits are 6.694 MW and 2.975 MW after using SMES, i.e., the fluctuation is reduced by 59.24 %.

On the other hand, WPG system needs to a large value of reactive power which it absorbed from the grid without SMES, this value of reactive power reached 7 MVAR during wind gust period. After using SMES with WPG system, the line reactive power is compensated, additionally, the absorbed reactive power from the utility grid is reduced to only 1 MVAR by using the SMES. As a consequence of the impact SMES reactive power, a great improvement is achieved in reactive power absorbed from the AC side. The average value of the absorbed wind reactive power from the grid is decreased from 4.163 MVAR to 0.9516 MVAR after using SMES (i.e. the reduction of absorbed reactive power from the grid is 77.14 %).

The response of SMES active and reactive powers is described in Fig. 11. It is clear that SMES could charge/discharge active power with fast response to face the variations of load and wind speed. On the other side, the SMES reactive power is injected at PCC bus to compensate the load reactive power besides improving the variation of PCC bus voltage due to wind gust and the change in load demand. The behavior of SMES energy stored, the voltage of DC capacitor and the voltage across the SMES coil are highlighted in Figs. 12-14, respectively. Fig. 12 illustrates the behavior of the SMES energy in both charging and discharging modes of operation to compensate the load at both wind speed and load variations.

The SMES stored energy increased/decreased and it does not exceed the rated value during charge/discharge modes. Also, the voltage of the DC-linked capacitor is nearly fixed at 2.4 kV during all modes of operation, as shown in Fig. 13. The investigation of the control process is approved by the fixed value of the voltage across the capacitor. Finally, the SMES coil voltage is changed negatively/positively according to discharging/charging modes, respectively, as shown in Fig. 14.

To demonstrate the superior effectiveness of the proposed control method, the obtained results in the paper are totally compared with the achieved results listed in [14, 19], which summarized in Table 5. The line real power fluctuation is reduced by 35 %, 56.53 % in [14, 19] respectively, while it is decreased by 59.24 % in the proposed method. On the other hand, the transmission line reactive power flow at PCC bus is reduced approximately by 55.56 %, 31.13 % in [14, 19], respectively, it has reduced by 77.14 % in the proposed method. The proposed control indicated that with a small contribution of SMES energy, a better reduction in line real and reactive powers fluctuations which flow between PCC bus and WPG is accomplished.

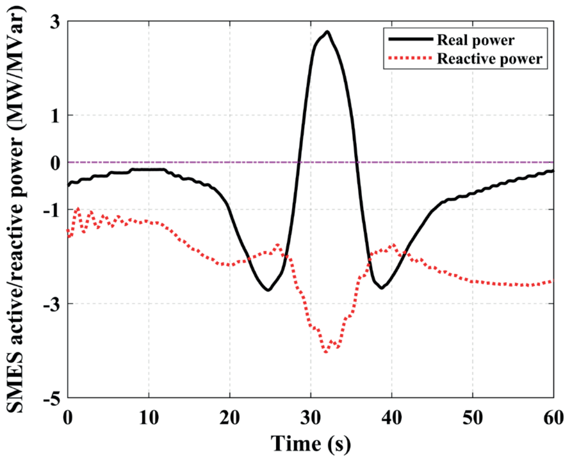

Fig. 11 SMES active and reactive power response

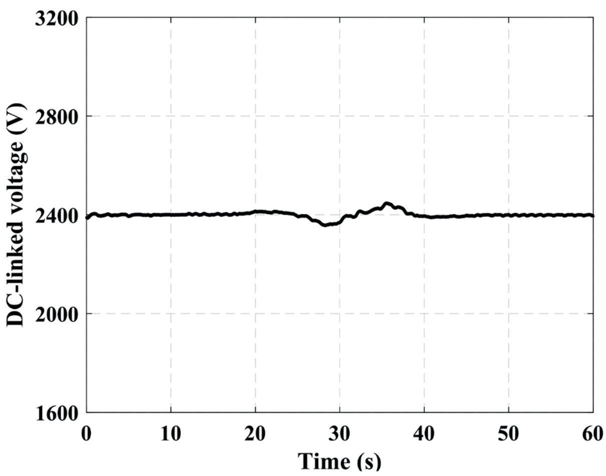

Fig. 13 Response of DC-link voltage

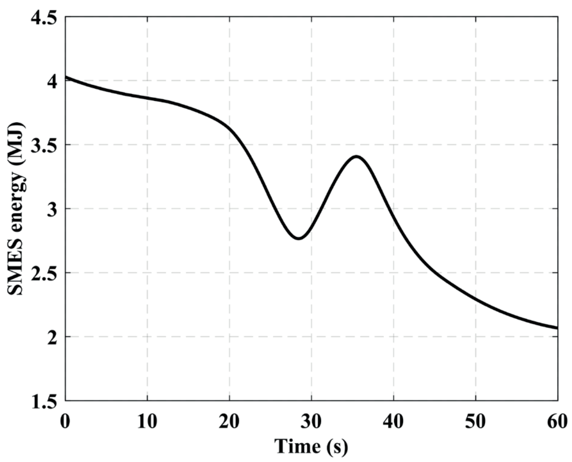

Fig. 12 The response of SMES energy

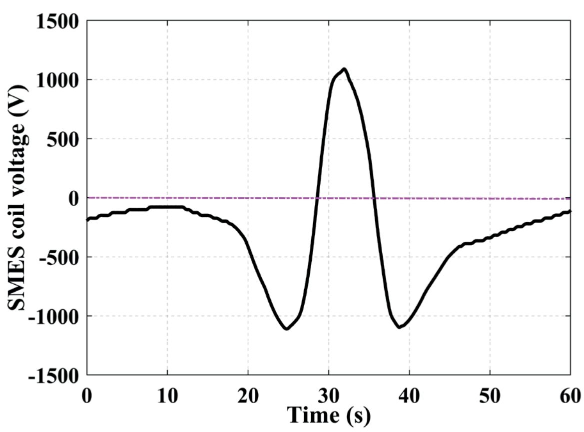

Fig. 14 Response of SMES coil voltage

Table 5 The detailed comparison of SMES impact for improving the exchange power applications

	[19]	[14]	Proposed method
Penetration of SMES with respect to total wind power generation (MW)	150 MJ, 66 MW Penetration = 227.27%	4.5 MJ, 9 MW Penetration = 50%	4.5 MJ, 9 MW Penetration = 50%
Penetration of SMES with respect to total system load (MVA)	Total load = 62.64 MVA Penetration =239.46%	Without load	Total load = 5.29 MVA Penetration = 85.07%
Type of wind speed fluctuations	Slow and small	Fastly and High	Fastly and High
Line active power variations	Decreased with 35%	Decreased with 53.1% in Scenario# 1 Decreased with 56.53% in Scenario# 2	Decreased by 59.24%
Average transmission line reactive power	Reduced by 55.56%	Reduced by 27.45% in Scenario# 1 Reduced by 31.13% in Scenario #2	Reduced by 77.14%
PCC bus voltage	Mitigated to its rated value (1.0 pu)	Mitigated to its rated value (1.0 pu)	Mitigated to its rated value (1.0 pu)

6 Conclusion

This work discussed a developed control approach of SMES system for controlling its active and reactive powers to regulate voltage and power interchange of a grid-connected WPG during the wind gust and the variations of load power. Both of WPG and SMES are connected at the PCC bus. The power transmitted between the PCC bus and SMES coil is controlled with the proposed FLC of the chopper circuit. FLC is designed in order to enable SMES rapidly charge/discharge both of active and reactive powers to compensate the fluctuation of voltage, line real power, and line reactive power at PCC bus. The summation of wind power fluctuation and load power variation is considered as the first input of FLC, the second input of FLC is the variation of SMES current.

The obtained results displayed the effectiveness of the proposed method in mitigating the PCC bus voltage and improving the power interchange between WPG and AC side during the extreme wind gust and the load fluctuations. With the proposed FLC method, SMES has success to rapidly discharge and charge the stored energy during high wind fluctuation and randomly load variation. This, in turn, helped in regulating the PCC bus voltage to the acceptable standard limits. It also success to mitigate the line active and reactive powers transfer between WPG and PCC bus during the extreme variations of wind speed and load profile changes. The SMES presented a good response during charging, standby, and discharging modes of operation which confirms the validation of the proposed control technique.

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