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# A robust SMES control for enhancing stability of distribution systems fed from intermittent wind power generation

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**Abstract:** The voltage and frequency stability issues of power systems are the main challenges that arise from high penetration levels of wind energy systems. This paper presents an effective solution for voltage and frequency stability problems by using a superconducting magnetic energy storage (SMES) system controlled with a fuzzy logic controller (FLC). The proposed control system can suppress the voltage and frequency fluctuations due to the high variations of wind speed. In addition, the proposed control system is suitable for both balanced and unbalanced distribution systems with high penetration levels of wind turbines (WTs). A squirrel cage induction generator (SCIG) is selected in the case study, which represents the worst scenario of WT generation from the voltage and frequency stability aspects. This is due to the high reactive power consumed by the SCIG from the utility grid during steady state and voltage fluctuations that may lead to harmful consequences for power system components. The proposed control method is validated using the IEEE 33-bus radial distribution network (RDN), wherein the SMES and WT systems are connected to the weakest points of the RDN. The obtained results demonstrate the superior performance of the proposed FLC-SMES system for alleviating the voltage and frequency fluctuations of the distribution power system during high variations of wind power.

**Key words:** Fuzzy logic control, superconducting magnetic energy storage, distribution systems stability, wind power generation

## 1. Introduction

Recently, new renewable energy resources (RERs) have become the most convenient sources in replacing fossil fuels. RERs possess several merits over conventional generation sources, such as being clean and unpolluted, renewability, and not requiring expensive maintenance [1–3]. The most vastly widespread RERs are wind, solar photovoltaic (PV), biomass, hydropower, and geothermal energy systems. Wind energy has been given global attention due to its high-power generations of up to 10 MW in a single wind turbine, the low cost of generated kWh, and being environmentally friendly. Therefore, wind energy systems are suitable for high penetration levels of RERs that may lead to full replacement of conventional energy sources [4–7].

However, high penetration levels of wind energy have led to frequency and voltage instabilities in utility grids due to the intermittent nature of wind power [8, 9]. Furthermore, the high penetration levels of large wind farms may act as adverse effects on the electrical grid under abnormal faulty conditions [10]. Thus, voltage stability, frequency stability, and damping oscillations have been highlighted as critical challenges to the integration of wind energy with high penetration levels in utility grids. Frequency stability is considered one

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of the major issues that face electrical power systems, wherein the knowledge of the frequency deviation ($\Delta f$) value is of prime importance for measuring the level of the system stability. Preserving the frequency stability can be achieved through the power balance between the generation and the load-demand sides. In addition, the existence of heavy loads and low power factor loads represents another challenge for voltage instability problems in many electrical networks. These factors directly affect the power transfer capability and reliability of the power system [11–13].

There are several attempts in the literature to provide solutions for solving voltage and frequency instability issues. The flexible AC transmission systems (FACTS) controllers are considered the most popular devices for supporting reactive power to enhance voltage stability [14, 15]. However, power system stabilizer (PSS)-based FACTS devices are needed for damping the oscillations [16]. Moreover, several optimization methods were employed in the literature for setting the parameters and locations of some FACTS devices, such as the thyristor-controlled series capacitor (TCSC) and static var compensator (SVC). This, in turn, can improve the voltage stability and minimize the active power losses [17]. Furthermore, on-load tap changing (OLTC) transformers were utilized for preserving an acceptable range of voltage at consumers' receiving points. This, in turn, can guarantee satisfactory operation and lifetime of the client apparatus. However, OLTC and FACTS strategies are not effective in the case of highly fluctuating wind generation systems, which may occur faster than the equipment handling time [18].

From another perspective, energy storage systems (ESSs), such as batteries [19, 20], flywheels [21, 22], pumped hydro [23, 24], etc., were employed in the literature for solving the frequency and voltage fluctuation problems. This can be done through charging and discharging operations of the ESSs to balance the power between RERs and loads. However, the battery and flywheel ESSs suffer from very slow responses in compensating power fluctuation. Moreover, they also have low efficiency and short lifetimes compared to superconducting magnetic energy storage (SMES) [25]. In addition, SMES systems have short time delay during charging/discharging processes, high efficiency, and long lifetime [26–28]. There are several proportional integral (PI) control methods developed for SMES systems to alleviate voltage sag/swell events and wind power generation transients [29]. However, these methods suffer from slow response and sensitivity to the system parameters [30, 31].

There are several control approaches for SMES systems in the literature. In [29], the conventional proportional-integral (PI) control method was employed. However, the presented method using a PI controller is not adaptive with the fluctuating behavior of wind generation and load demands. An improved self-tuning control method for SMES was provided in [32]. However, this controller lacks simple implementation and safe operation of SMES devices due to ignoring the state of charge (SoC) of the SMES system. Another model predictive-based control method was developed in [33] considering the SoC of the SMES. This method suffers from the complex implementation of its weighting factors and its dependency on the accurate power system model and parameters. Table 1 summarizes the contribution of this paper with the most featured research in the literature.

Motivated by the aforementioned drawbacks in the existing attempts in the literature, this paper proposes a new robust control method based on a fuzzy logic-controlled SMES system. The proposed system and controller can enhance the voltage and frequency instabilities of power systems with high penetration levels of wind energy. Furthermore, the proposed system is validated using the IEEE 33-bus distribution system with 30% penetration level (i.e. with respect to loading power) of the wind energy systems. A squirrel cage induction generator (SCIG)

**Table 1**. Contributions of this paper with the most featured research in the literature.

| Reference | Methodology | Mitigating fluctuations | SMES SOC | Distribution system | Complexity |
|---|---|---|---|---|---|
| Ref [29] | PI control method | x | x | Balanced | Low |
| Ref [32] | Self-tuning control method | ✓ | x | Balanced | High |
| Ref [33] | Model predictive control | ✓ | ✓ | Balanced | Very high |
| Proposed | SMES device controlled by FLC | ✓ | ✓ | Balanced/unbalanced | Low |

is selected as a case study in this paper because it represents the worst wind generation scenario. This is because it requires high reactive power during fluctuations in comparison with the other wind generators. The selected case study includes both balanced and unbalanced radial distribution networks (RDNs). The validated system shows a great enhancement of the voltage and frequency stability, which is obtained by installing the proposed SMES system and controller in both balanced and unbalanced distribution systems. From the above discussion, the main contributions of this paper can be summarized as follows:

- This paper presents an effective solution for mitigating voltage and frequency stability problems based on employing the SMES system. The proposed system benefits from the advantage of enhancing the voltage variation of the distribution system to a specified acceptable limit (i.e. ±5% of the rated value).
- An improved controller design method for SMES systems is presented based on the FLC method for damping the overshoot and undershoot spikes of the system frequency due to the transient speed variation of the high penetration level of wind power generation.
- The proposed system and controller are capable of improving the performance of three-phase balanced and unbalanced distribution systems considering the high wind speed variation and large unbalanced loading conditions.
- The proposed solution has the advantage of reducing the grid reactive power required for the SCIG excitation circuit by injecting the reactive power by the SMES. Therefore, the transmission line power losses are reduced in accordance to the local supply of the reactive power.

The remaining part of the paper is organized as follows: Section 2 introduces the voltage and frequency problems impacted by wind power fluctuations. Section 3 details the modeling of the selected case study, including the studied system and the wind power generator. Section 4 presents the proposed SMES system and FLC method. Comparative studies and results to validate the effectiveness of the proposed SMES system and FLC method are presented in Section 5. Finally, Section 6 summarizes the obtained results and conclusions.

## 2. Problem description

### 2.1. Frequency stability problem

The frequency stability of the power system can be maintained according to the active power balance between the generation and load demand sides. There are several additional factors that may affect the frequency stability, such as sudden load variations in the power system in which the frequency fluctuates until the aggregate generation in the system meets the new load condition. Furthermore, the increased installations of wind energy sources are adversely affecting the frequency stability of the system, which results from the low inertia property of wind systems. Hence, a power system with high penetration levels of wind energy generation is expected to face more frequency stability challenges.

### 2.2. Voltage stability issue

The voltage stability is related to the balance of reactive power loading and reactive power capability within a power system. Voltage dips occur in the power system in the case of reactive power unbalance. In a similar way to the frequency stability problem, the unbalanced loading can lead to unbalanced voltage drop. This in turn increases the current drawn by inductive loads and the rotor heating due to the negative sequence magnetic flux. This flux generated in the stator opposite to the rotor rotation induces negative sequence voltage on the shorting bars. Thence, negative sequence short-circuit current flows in the rotor. Moreover, the false operation of protective devices may trip the system due to the high resultant current flowing in the neutral line at earth fault. These factors directly increase the required reactive power support.

### 2.3. Wind power fluctuations

The fluctuating nature of the wind power generation comes from its dependence on the weather situation and the natural change of wind turbine speed. These fluctuations in wind speed impose serious challenges to power system designers and operators. Fluctuations in the frequency and voltage of power systems, low power system inertia, and accurate protective relays settings are the main consequences of the variable nature of wind generation systems. In addition, wind energy is a noncontrollable energy source that causes problems with voltage stability and transient stability. Consequently, several performance criteria of the power system are influenced, such as the power system operation point, the power flow of active and reactive power, nodal voltages, and power losses of the system.

## 3. Modeling of power system

### 3.1. Studied system model

Figure 1 shows the single-line diagram of the studied IEEE 33-bus distribution system. The selected case study considers the system data of loads and line impedances as given in [34]. This case study of the power system is studied under two conditions: balanced loading and unbalanced loading. The case study of unbalanced loading is emulated by unequal division of the electrical loads on the three phases with 30%, 20%, and 50% of full loading between phases A, B, and C, respectively. The designed SMES units and the wind power generation system were placed at buses 18 and 33, which represent the weakest points of the distribution system. The parameters of the SCIG and SMES model are summarized in Table 2 and Table 3, respectively. The initial SoC of the SMES system is assumed to be 50% of its maximum value (320 kJ).

**Table 2**. Parameters of the SCIG system.

| Component | Symbol | Value |
|---|---|---|
| Power rating | MVA | 0.6/0.9 |
| Voltage | $V_{rms}$ (V) | 480 |
| Rotor resistance | $R_r$ (pu) | 0.01909 |
| Magnetizing reactance | $X_m$ (pu) | 1.354 |
| Stator resistance | $R_s$ (pu) | 0.01965 |
| Stator reactance | $X_s$ (pu) | 0.0397 |
| Rotor reactance | $X_r$ (pu) | 0.0397 |

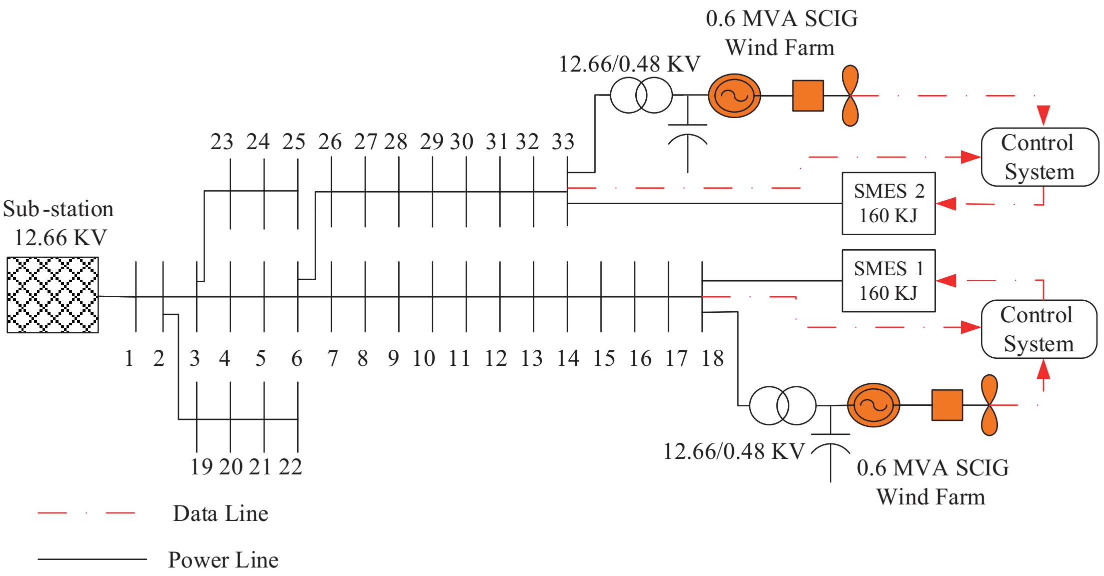


**Figure 1**. The selected case study of IEEE 33-bus radial distribution system.

**Table 3**. Parameters of the SMES system.

| Component | Value |
|---|---|
| SMES energy ($E_{SMES}$) | 160 kJ |
| SMES current ($I_{SMES}$) | 800 A |
| SMES inductance ($L_{SMES}$) | 0.5 H |
| DC link capacitor | 20 mF |

### 3.2. Modeling of SCIG wind power generation

The SCIG is selected as a wind turbine generation system in the studied case. Figure 2 shows the complete system of the wind power generation. A capacitor bank is normally connected to the SCIG system in order to inject the required reactive power for improving its power factor. The generated wind power of the turbine can be determined using Eq. (1) as follows [35]:

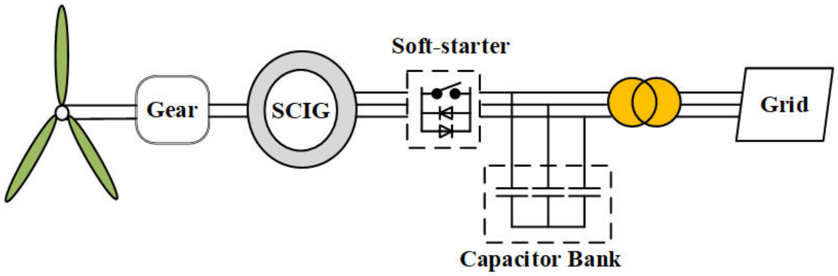


**Figure 2**. Schematic diagram of the SCIG wind turbine system.

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

where $A$ represents the area covered by the rotor, $\rho$ is the air density, $\upsilon$ denotes wind speed, $C_p$ is the performance coefficient of the turbine, $\lambda$ represents the tip speed ratio of the rotor blade tip speed to wind speed, and $\beta$ is the blade pitch angle (in degrees). The pitch angle control method can be employed for stabilizing the generator output power to an acceptable limit during high wind speeds. In the pitch angle control method, the pitch angle is preserved at zero degrees if the measured output power is lower than its nominal value whereas the controller increases the pitch angle to maintain the measured output power to its nominal limit if the output power is increased. The coefficient $C_p(\lambda, \beta)$ of SCIG wind power generation is given using Eq. (2) as follows [36]:

$$C_p(\lambda, \beta) = C_1(\frac{C_2}{\lambda_i} - C_3\beta - C_4)e^{-\frac{C_5}{\lambda_i}} + C_6\lambda_i, \tag{2}$$

where $\lambda_i$ can be computed as follows:

$$\frac{1}{\lambda_i} = C_1(\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}), \tag{3}$$

where the coefficients values of $C_1$ to $C_6$ of the selected case study are given in [37].

## 4. The proposed SMES system and FLC method

### 4.1. Proposed method for mitigating voltage/frequency fluctuations

This paper proposes an improved method and new application of a SMES system to mitigate the frequency and voltage fluctuations in distribution systems with high penetration levels of wind energy. The existence of the high penetration levels of wind power results in the shortage of real and reactive power controls. Indeed, the control of active and reactive power is essential in order to preserve stable frequency and voltage within limits, whereas the lack of reactive power can lead to voltage dip problems and no control in the active power can cause frequency deviations. Therefore, this work proposes a performance improvement of distribution networks in two different situations: a balanced distribution system and an unbalanced distribution system, with controlling active and reactive powers of the SMES system.

### 4.2. SMES system and modeling

The SMES system consists of the superconducting coil (SC) as a magnet, cryogenic refrigerator, cryostat/vacuum vessel to preserve the coil in the superconductivity state, and a cooling protection system. The power conditioning system of the SMES is shown in Figure 3. It contains a DC-DC chopper, DC-link capacitor, bidirectional voltage source converter (VSC), and coupling transformer. The energy is stored as a magnetic field created by the direct current flowing through the SC. In addition, the SC should be maintained within the superconductivity state by immersion in liquid helium at 4.2 K in an insulated vacuum cryostat. The proposed FLC method is used to control the DC-DC chopper. SMES action is determined by adjusting the duty cycle command (D), which is compared with 1 kHz sawtooth signal to switch ON/OFF the switches of the DC-DC chopper. Moreover, the bidirectional VSC is employed to interface the SMES with the distribution system and to control their energy exchange. The bidirectional VSC is controlled using the synchronous d-q reference frame, which is detailed in [38, 39]. The stored energy and the output power of SMES are calculated using Eqs. (4) and (5), respectively, as follows:

$$E = \frac{1}{2} L_{SMES} I_{SMES}^2, \tag{4}$$

$$P = \frac{dE}{dt} = L_{SMES} I_{SMES} \frac{dI_{SMES}}{dt} = V_{SMES} I_{SMES}, \tag{5}$$

where $E$, $I_{SMES}$, $V_{SMES}$, and $L_{SMES}$ represent the initial SMES energy, initial SMES current, voltage of the SMES coil, and SMES coil inductance, respectively.

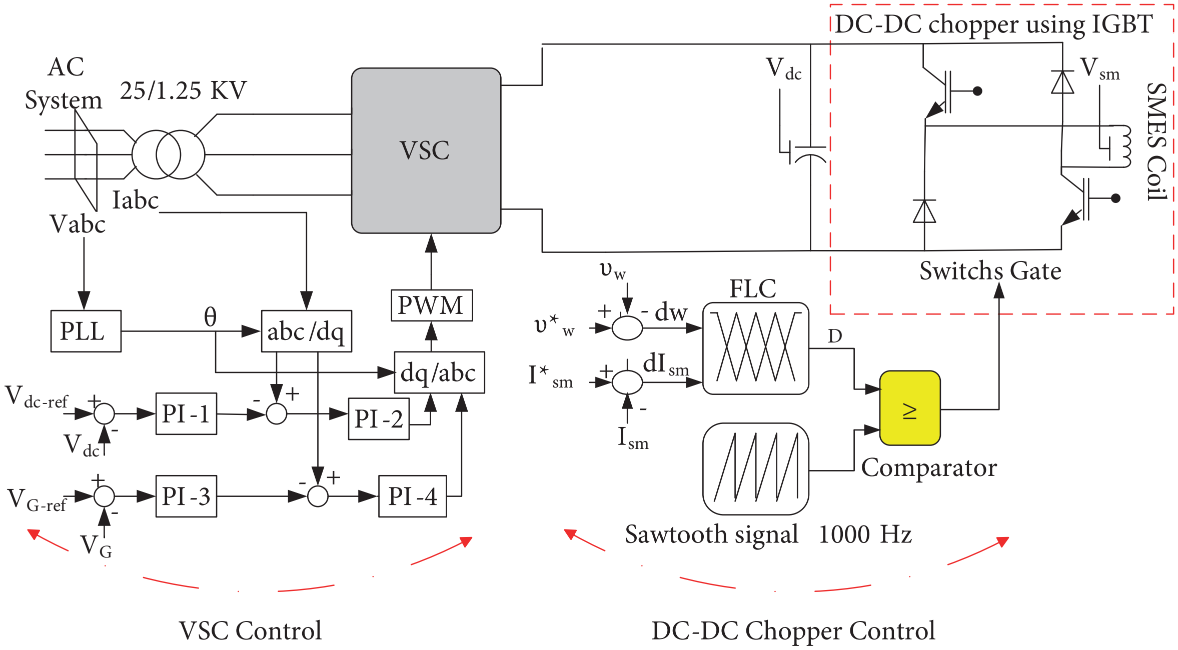
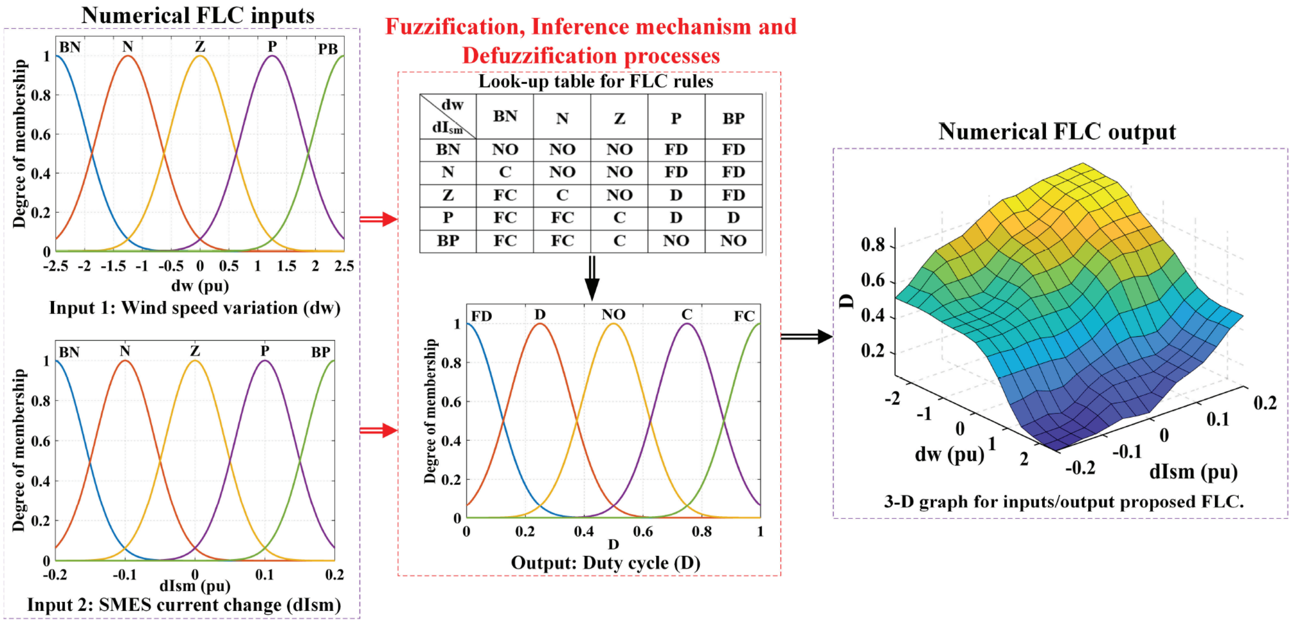


**Figure 3**. The proposed SMES system and controller.

### 4.3. The proposed FLC method

The proposed FLC method is employed for improving the SMES control behavior so that the SMES can smoothly perform the charging and discharging operations with the electrical distribution system. Moreover, the proposed enhanced FLC method considers simple implementation using only two inputs and one output membership function (MF). The first input is the variation of wind speed, which is the difference between actual wind speed and the reference wind speed. The second input is the change of SMES current, which is the difference between its reference value and its actual value. The output membership function of the FLC method is the duty cycle (D) of the DC/DC SMES chopper converter.

Figure 4 shows the proposed FLC controller with the input and output membership functions. In addition, Figure 4 includes the rules of the FLC and the 3D graph of the inputs-output relationship of the proposed FLC method. The design process of the input and output membership functions is based on the Gaussian membership function. The input MFs are represented using five different linguistic variables: big negative (BN), negative (N), zero (Z), positive (P), and big positive (BP). The output membership function is represented by using five linguistic variables: fast discharge (FD), discharge (D), no action (NO), charge (C), and fast charge (FC). The look-up rules-based proposed FLC method is shown in Figure 4. If-then rules of fuzzy logic are implemented using the rule table. Then the maximum of the minimum composition scheme is utilized for the interference stage. The center of gravity (COG) scheme is used for implementing the defuzzification process.



| $dI_{sm}$ \ dw | BN | N | Z | P | BP |
|---|---|---|---|---|---|
| BN | NO | NO | NO | FD | FD |
| N | C | NO | NO | FD | FD |
| Z | FC | C | NO | D | FD |
| P | FC | FC | C | D | D |
| BP | FC | FC | C | NO | NO |

**Figure 4**. The complete schematic diagram of the proposed FLC method for the SMES system.

The SMES system is managed through the control signal from the proposed FLC method according to the output power of the wind generation and load demand. The SMES system possesses three main operating modes in the distribution system, as follows:

- Charging mode: The SMES operates in charging mode when the wind-generated output power is larger than the load demanded power until the SMES reaches the full charge situation. In this mode, the SMES DC/DC converter operates with duty cycle D in the range of $0.5 > D \geqslant 1.0$.
- Discharging mode: The SMES operates in discharging mode when the load demanded power exceeds the wind generated output power until the SMES reaches the full discharge situation. In this mode, the SMES DC/DC converter operates with duty cycle D in the range of $0.0 \geqslant D > 0.5$.
- Standby mode: The SMES operates in standby mode when the SMES does not have any charging or discharging operations and it is kept in the standby mode. In this mode, the SMES DC/DC converter operates with duty cycle D in the range of $D = 0.5$.

## 5. Results and discussion

The proposed SMES system and FLC method were implemented using the MATLAB program. The selected case study is based on the IEEE 33-bus system as shown in Figure 1. The SMES and SCIG wind turbine were installed at the weak buses of the system (buses 18 and 33). The impacts of the SMES system for smoothing power generated and enhancing frequency/voltage fluctuations were studied with intermittent 30% wind penetration with respect to system load power. Table 2 and Table 3 summarize the developed system parameters for the selected case study. The system was tested at enormous variations of wind speed, which is shown in Figure 5. Voltage profiles of other buses have not been mentioned in the results as they possess better profiles than the selected weak buses. Moreover, the study is implemented considering both balanced and unbalanced distribution systems.

### 5.1. Balanced distribution system analysis

This section presents the results of frequency fluctuations and voltage profiles at buses 18 and 33 taking into consideration wind speed variations as shown in Figure 5, and the loads are equally distributed between the three phases. The voltage profiles at buses 18 and 33 are shown in Figure 6a and Figure 6b, respectively, considering three cases: (1) without installing wind or SMES systems, (2) installing wind generation only, and (3) installing both wind generation and SMES systems. It is clear that the voltage profiles are significantly improved by using the SMES. The voltage magnitude at bus 18 has increased from lower than 0.92 pu in the case of no SMES to about 1.02 pu with installing the proposed SMES and controller. In addition, the voltage magnitude has been improved at bus 33 to nearly 1.0 pu with installing the SMES system. Furthermore, the effectiveness of the proposed enhanced design of the FLC method has become clear as the frequency deviations have been damped rapidly to the steady-state value.

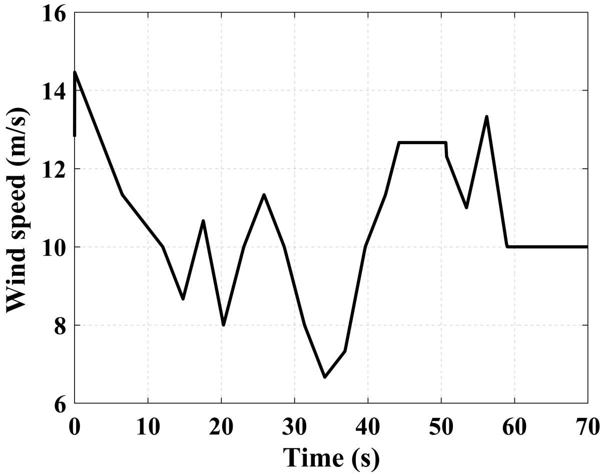


**Figure 5**. The profile of wind speed for the selected case study.

The ability of the proposed system and controller to damp the power system overshoot and undershoot spikes is shown in Figure 7. It can be seen that the proposed FLC method has smaller overshoots and undershoots than that without using the SMES. This can be interpreted due to the high and fast response of the SMES system. Moreover, the proposed system and controller are able to stabilize the power system faster than the traditional power system not using the SMES. Therefore, enhanced frequency stability is achieved by installing the designed SMES and the proposed FLC method.

Figure 8a shows the active and reactive power exchange of the installed SMES for the selected case study. The proposed SMES system charges real power at high wind speed and discharges real power during low wind speed. Hence, it is capable of compensating the variation of the frequency profile of the selected case study. Additionally, the SMES system can inject/absorb reactive power to regulate the voltage profiles for all buses of the distribution system during wind speed variation. The charging/discharging of real/reactive powers are controlled so that the voltage at all buses remains at acceptable values (±5% of rated value) during wind speed

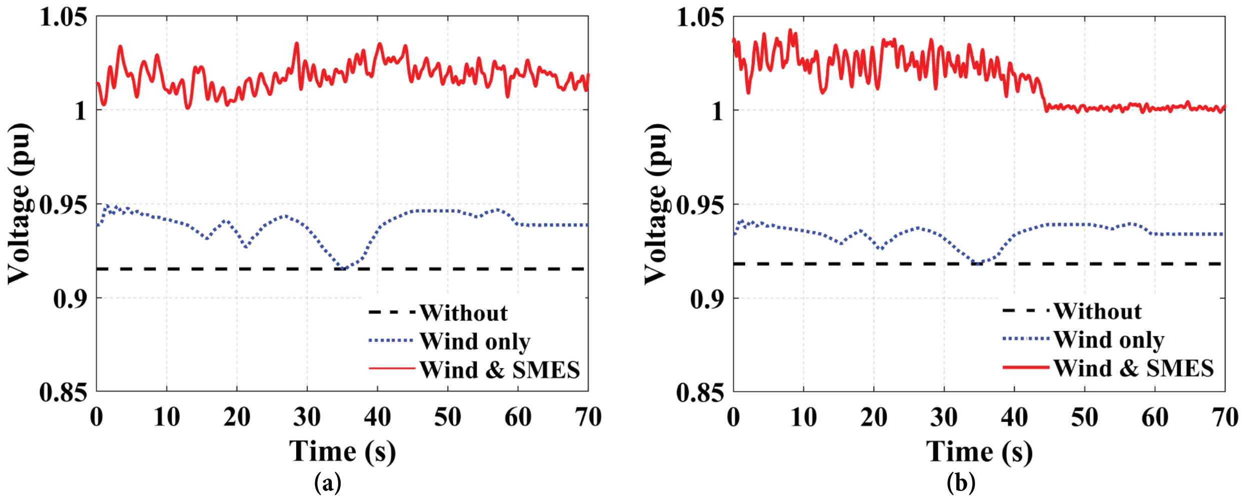


**Figure 6**. Voltage profiles for the selected case study with balanced distribution system at (a) bus 18 and and (b) bus 33.

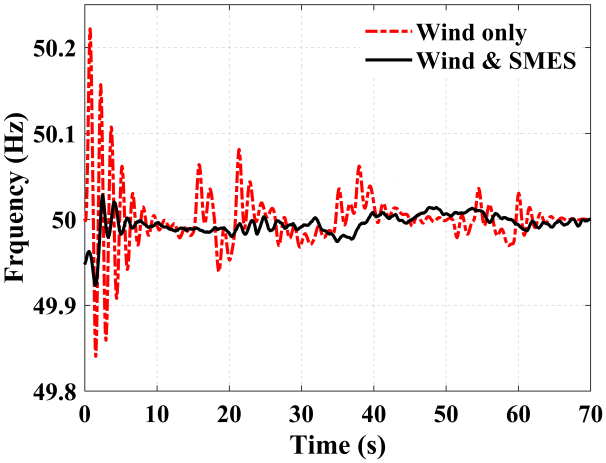


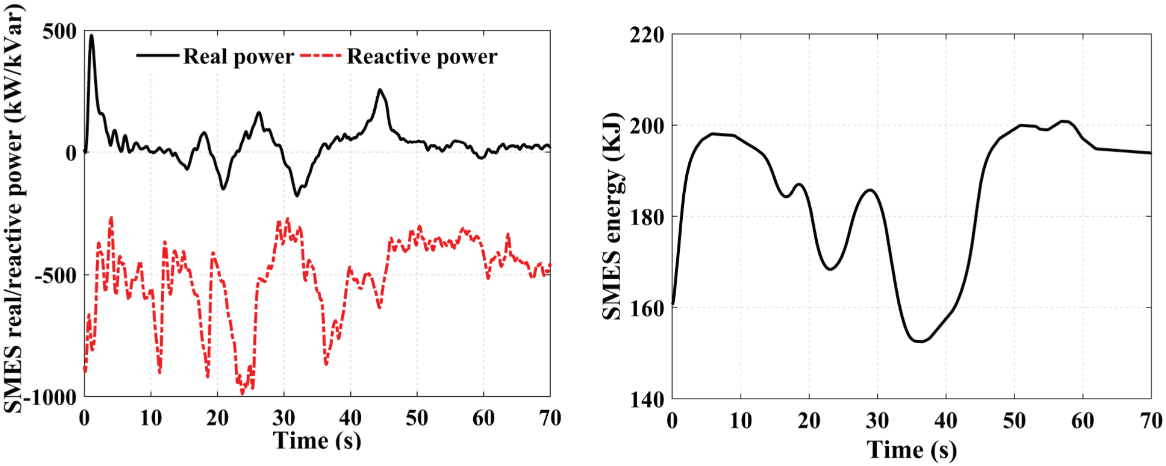
**Figure 7**. Performance of the frequency profile of the selected case study with balanced distribution system.

variation. The corresponding stored energy in the SMES system is shown in Figure 8b. The stored energy increases/decreases around its rated value to compensate the fluctuation in the voltage and frequency profiles.

### 5.2. Analysis of unbalanced distribution system

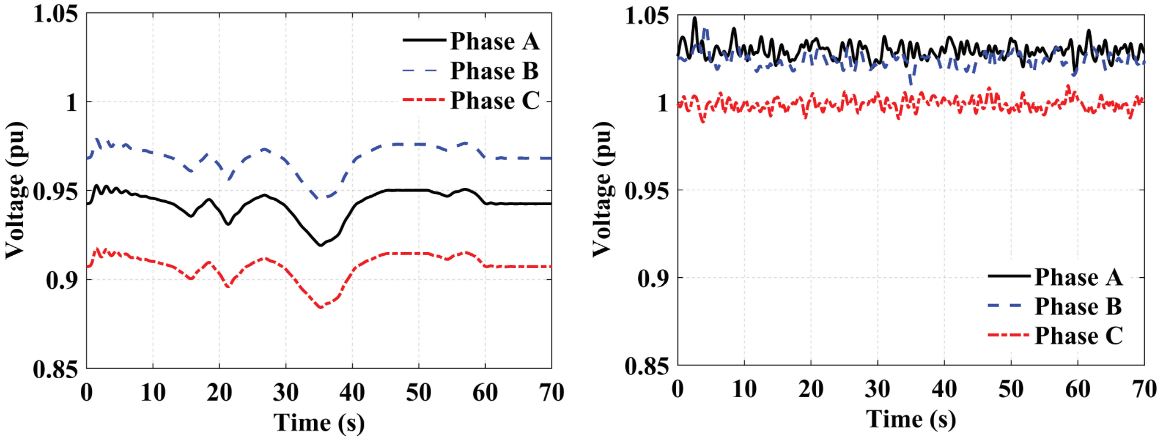
The performance of the proposed SMES system and FLC method is also investigated with the unbalanced distribution system. The unbalanced condition is emulated through the unequal distribution of loads among the phases with 30%, 20%, and 50% of the total loads for phases A, B, and C, respectively. The comparison of three-phase voltage profiles between a traditional power system without SMES and with installing the SMES for buses 18 and 33 is shown in Figure 9 and Figure 10, respectively.

The superior performance of the distribution power system with the proposed SMES and controller in maintaining the voltage profiles of both buses at the system limits of 5% tolerance is clear. For the voltage profile at bus 18, voltage magnitude has increased from 0.93, 0.94, and 0.89 pu to 1.03, 1.03, and 1.0 pu for



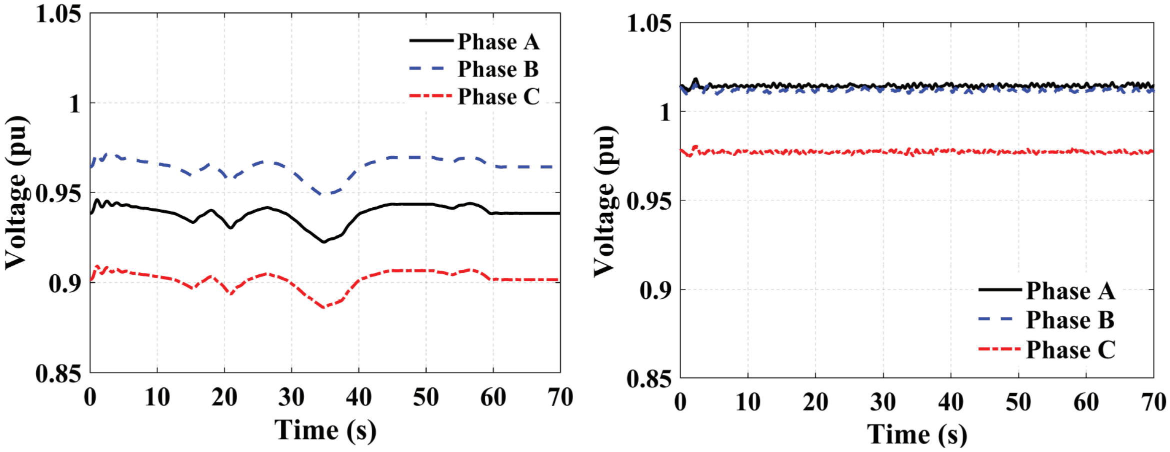
(a) (b)

**Figure 8**. Performance of SMES with balanced distribution system scenario: (a) real and reactive power profiles; (b) stored energy.



(a) (b)

**Figure 9**. The voltage profiles of the three-phase distribution system at bus 18: (a) without SMES; (b) with the proposed SMES system and FLC controller.



(a) (b)

**Figure 10**. The voltage profiles of the three-phase distribution system at bus 33: (a) without SMES; (b) with the proposed SMES system and FLC controller.

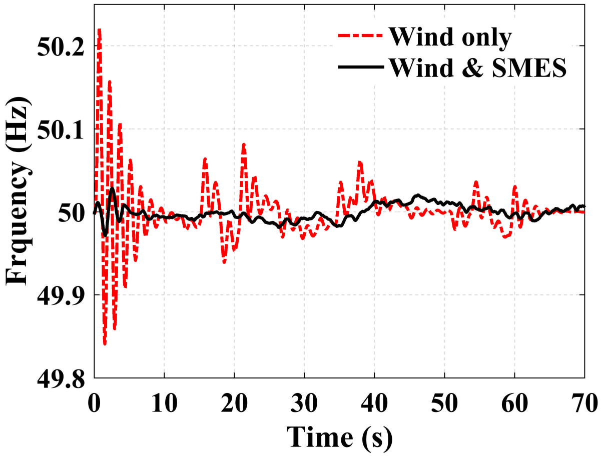


**Figure 11**. Performance of the frequency profile of the selected case study with the unbalanced distribution system.

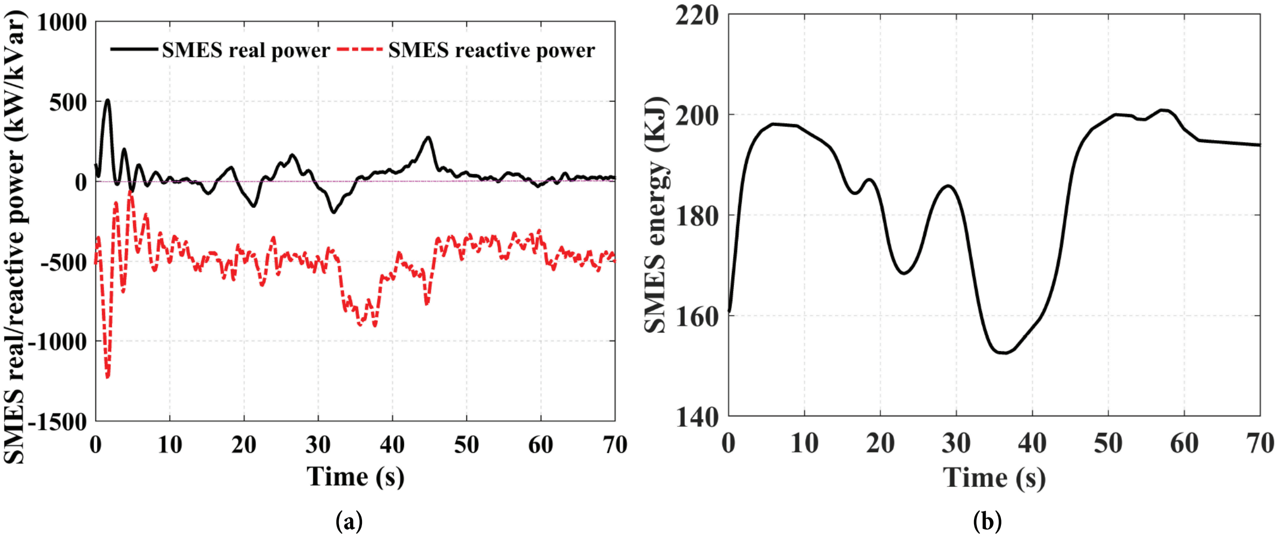


**Figure 12**. Performance of SMES with unbalanced distribution system scenario: (a) real and reactive power profiles; (b) stored energy.

phases A, B, and C, respectively. In addition, the voltage magnitude at bus 33 has improved from 0.93, 0.95, and 0.89 pu to 1.02, 1.02, and 0.98 pu for phases A, B, and C, respectively. Thus, the proposed system and controller are suitable for balanced and unbalanced distribution systems operations.

Furthermore, Figure 11 compares the behavior of frequency fluctuation between traditional power systems without SMES and the proposed controlled SMES system for unbalanced distribution systems. It can be seen that the proposed SMES and FLC controller are able to effectively damp the frequency fluctuations in the system. Additionally, the steady-state value with installing the SMES is stabilized faster than in traditional power systems without SMES. Therefore, the proposed FLC-SMES is feasible under unbalanced distribution systems operation and the enhanced damping of frequency fluctuations of the power system is obtained.

The real and reactive power profiles of the SMES system are shown in Figure 12a, and the associated SMES energy profile is presented in Figure 12b. It can be seen that the SMES can rapidly exchange power to stabilize the system in comparison with the other ESSs. The proposed SMES can discharge/charge real power at low/high wind speeds to improve the frequency variations. Moreover, the proposed SMES and FLC method can inject/absorb reactive power to support the voltage profiles and regulate it within the acceptable limits. It is clear from Figure 12b that the SMES energy has not exceeded its maximum rated value during the charging and discharging operations. Thus, the proposed SMES system can compensate the variation of the frequency profile of the selected case study in unbalanced distribution systems. The proposed FLC can also preserve reliable operation of the SMES device according to its safe thermal and electrical constraints.

Therefore, it can be concluded from the previous results and discussion that the proposed SMES system and controller are capable of suppressing various voltage and frequency fluctuations resulting from the high variations of wind speed and load demands. The main benefits of the proposed controller are as follows:

- The proposed control system is suitable for both balanced and unbalanced distribution systems with high penetration levels of wind turbines.
- The proposed controller is capable of suppressing the various types of voltage and frequency variations, which result from the highly fluctuating nature of wind generation and load demands.
- The proposed SMES system and controller are capable of mitigating voltage and frequency stability problems. The proposed system preserves the specified acceptable limit (i.e. ±5% of the rated value) for the PCC voltage variation of the distribution system.
- The proposed system and controller are beneficial for both balanced and unbalanced loads, which verifies the generality of the proposed system.

## 6. Conclusions

This paper presented an improved SMES system and FLC method for mitigating voltage and frequency stability problems associated with the fluctuating nature of wind energy systems. The proposed system and controller can enhance the voltage and frequency instabilities of distribution power systems with high levels of wind energy penetration. Moreover, the proposed system and controller can be applied to various types of wind energy generation systems and to both balanced and unbalanced distribution systems. The proposed system is validated using the IEEE 33-bus distribution system with 30% penetration level of wind power generation. The results proved the superiority of the proposed FLC-SMES method in various operating modes and conditions. The effectiveness of the proposed system and controller in suppressing the existing voltage and frequency fluctuations in the traditional distribution power systems has become clear. Furthermore, the proposed FLC method is advantageous in preserving the reliable operation of the SMES system and protecting it from overloading and thermal stresses conditions.

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