IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received June 12, 2019, accepted June 27, 2019, date of publication July 10, 2019, date of current version July 25, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2927902

SMES-Based Fuzzy Logic Approach for Enhancing the Reliability of Microgrids Equipped With PV Generators

SAYED M. SAID[1,2], MOKHTAR ALY[1,3], (Member, IEEE), BÁLINT HARTMANN[2], (Member, IEEE), ABDULLAH G. ALHARBI[4], (Member, IEEE), AND EMAD M. AHMED[1,4], (Senior Member, IEEE)

[1]Department of Electrical Engineering, Aswan University, Aswan 81542, Egypt
[2]Faculty of Electrical Engineering and Informatics, Budapest University of Technology and Economics, 1111 Budapest, Hungary
[3]Solar Energy Research Center (SERC-Chile), Universidad Tecnica Federico Santa Maria, Valparaiso 2390123, Chile
[4]Department of Electrical Engineering, Jouf University, Sakaka 72388, Saudi Arabia

Corresponding author: Emad M. Ahmed (emad@eng.aswu.edu.eg)

This work was supported in part by the SERC Chile under Grant CONICYT/FONDAP/15110019 and in part by the AC3E under Grant CONICYT/BASAL/FB0008.

ABSTRACT The fluctuated nature represents the main obstacle for increasing the penetration level of photovoltaic (PV) generators in utility microgrids. The energy storage systems (ESSs) represent the main solutions to get over these fluctuations. Among various ESSs, the superconducting magnetic energy storage (SMES) systems have proven themselves as an effective solution. The SMES control systems in the literature result in a shortened lifetime, degraded thermal behavior, and high AC losses in the SMES. Thence, reliable operation of SMES systems and microgrids has been given wide concerns due to the large fluctuations in microgrids with high levels of PV penetrations. This paper presents a SMES-based fuzzy logic approach for improving the reliability of SMES and utility microgrids with high PV penetration levels. The proposed SMES controller employs the state of charge (SOC) of SMES as an input. This, in turn, can effectively extend the lifetime of SMES due to eliminating the overcharge and deep discharge operating states. Moreover, the proposed system controls smoothly the SMES current using the fuzzy rules' system. The superiority and effectiveness of the proposed SMES controller are verified using simulation-based case studies of utility grids with high PV penetration levels. The obtained results show the effective smoothing of fluctuated power and constant bus voltages in the studied microgrid under the proposed controller. In addition, the proposed SMES controller provides superior performance regarding the lifetime and reliability of the SMES systems and microgrid components.

INDEX TERMS Fuzzy logic control, microgrids, PV generators, state of charge, superconducting magnetic energy storage.

I. INTRODUCTION

Recently, the yearly growth rate of photovoltaic (PV) generation has been largely increased, reaching of the total generation of 227 GW in 2015 compared with a total generation of 177 GW in 2014. It is expected that there will be continuous increase in PV generation to achieve between 1760 to 2500 GW by the year 2030 [1], [2]. Being available everywhere and environmental friendly, and achieving a continual decrease in their cost per watt benefits have made widespread PV systems compared to other renewable energy sources [3]. However, the generated power of PV systems is dependent on solar irradiance and ambient temperature, which change continuously during the daytime. The fluctuating nature of the PV generation systems results in continuous changing output power in addition to voltage rise problems. Therefore, the increased penetration levels of PV systems and their fluctuating nature have made their reliability, maximum energy harvesting, and integrating energy storage systems (ESSs) of the principal interests for research and industry [4]–[7].

The ESSs were adopted in the literature for smoothing the power fluctuations in microgrids with PV and wind

The associate editor coordinating the review of this manuscript and approving it for publication was Canbing Li.

generations [8]–[11]. Among various types of ESSs, the superconducting magnetic energy storage (SMES) systems are preferred due to their high power densities, quick response, high operational efficiency, and light environmental pollution [12]. Although, reliability concerns of SMES system have been increased when they are applied in power systems including PV generations. This is due to that the exchanged power by SMES causes AC loss in the SMES magnet, and heat is generated in accordance [13]. Thence, thermal stability of SMES coil is threatened. In addition, the continuously changing current of SMES leads to unstable power availability and capacity.

Major researches appertaining to reliable operation of SMES in power systems have been developed in the literature. Different aspects and design considerations of SMES in high power applications have been studied in [14]. A method combining electrical design and electromagnetic design was introduced in [15]. Whereas, advanced methods for power losses calculations of SMES as energy exchange devices were presented in [16]. Moreover, the transient thermal stability of SMES in power systems has been covered in the literature. Capability curve based design and protection scheme for SMES during transient overload condition was presented in [17]. Additionally, SMES status evaluation scheme was presented in [18] for assuring the better dynamic thermal stability of SMES in power systems. Using these methods, sharp temperature rise of SMES can be averted, while compromising the functionalities of SMES in the power system.

In [19], the model predictive controller (MPC) was proposed for controlling SMES systems in order to restrict the current through SMES within the allowable limits. However, dependency on accurate modelling, the complexity of adapting the weighting factors, and need for complex calculations especially in large power systems represent major restrictions on MPC method in SMES application. The proportional-integral (PI) controller was employed for SMES operation in [20]. However, the fixed gain property of PI controllers does not match the continually changing nature of the power systems. Self-tuning control methods using linear models and neural network were presented to fix the fixed gain problems of conventional PI controllers [21]. Although these controllers cannot guarantee better performance due to the lack of control constrains of the SMES devices. The application of Fuzzy-logic based controller for SMES in microgrids with PV generation systems was introduced in [22]. The fuzzy logic controller provides smooth and efficient control against the power fluctuations in microgrids. However, the severe fluctuated output power of PV generation systems results in overcharging and deep discharging states of SMES, which may cause its failures and shortened lifetime.

Motivated by the aforementioned insufficiency of the presented SMES controllers in the literature, this paper presents a new SMES controller based on Fuzzy logic control method with considering the state of charge (SOC) of SMES for enhancing its reliability. The short lifetime shortcoming of SMES can be effectively avoided using the proposed controller. Additionally, the proposed controller preserves constant bus voltages regardless of the fluctuated power of PV generation. Therefore, the reliability of the overall microgrid system can be improved. Moreover, the proposed controller design method can be generalized for different microgrid architectures. The main contributions of the paper are summarized as follows:

- A new SMES control method is developed to increase the reliability of the SMES device through utilizing the SOC of SMES device as an input.
- An improved method of efficiency improvement of transmission lines through local load supply by proper design of the combined PV-SMES system.
- Lifetime extension control method of power electronic capacitors is developed through avoiding fluctuated operating voltages due to deep charging and/or discharging operations.

The remaining of the paper is organized as follows: Section II presents the selected case study and its modeling. The proposed control method and its mathematical formulation are detailed in Section III. The simulation results of the selected case study are included in Section IV. Section V gives a comprehensive discussion and performance comparison for confirming the superiority of the proposed controller over the previously presented controllers. Lastly, the paper conclusions are provided in Section VI.

II. SELECTED CASE STUDY AND MODELLING OF PV SYSTEM

A. STRUCTURE OF THE STUDIED SYSTEM

Fig. 1 shows the configuration of the studied microgrid as a case study. The studied microgrid consists of 500 kW PV generation system, which is connected to the point of common coupling (PCC) bus through step up transformer. In addition, the SMES system is employed in the selected microgrid as an energy storage system. The SMES is connected to the PCC bus system through a step up transformer with rating 1.2/25 kV. The rating of the studied SMES system

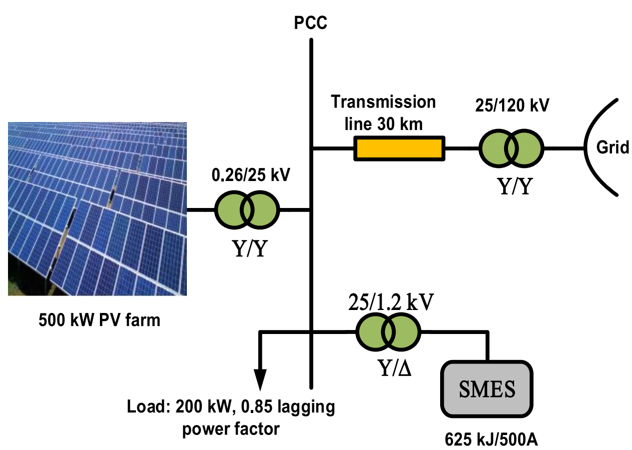

FIGURE 1. The selected case study of PV-SMES microgrid power system.

is 625 kJ/500 A. The microgrid has to feed its local load that is located at the same PCC bus with the ratings of 200 kW, 0.85 lagging power factor. The selected microgrid is connected through 30 km transmission line to the 120 kV utility power grid.

B. MODELING OF PV GENERATION SYSTEM

The modelling of PV system is usually employed for converting the irradiance and temperature of the sun into electricity. The PV array systems are modular and they consist of series and/or parallel connection of PV modules. The number of connected series and parallel modules in the PV array are determined according to voltage level requirements of the PV system and desired DC power output ratings of the array, respectively. The PV cell represents the basic component of the PV module system, which is composed from multiple series and parallel PV cells. Fig. 2 shows the equivalent circuit model of PV cell [23]. The dependency of the output current and output power of the PV cell on the PV model parameters are described using (1) and (2) as follows:

$$I = I_{pv} - I_o \left[\exp\left(\frac{V + R_s I}{\left(kT/_q\right) a} \right) - 1 \right] - \frac{V + R_s I}{R_p} \quad (1)$$

$$P_{cell} = V \left(I_{pv} - I_o \left[\exp\left(\frac{V + R_s I}{\left(kT/_q\right) a} \right) - 1 \right] - \frac{V + R_s I}{R_p} \right) \quad (2)$$

where V, I, I_{pv}, I_0, R_s, R_p, q, K, T, and a are terminal voltage, current of PV cell, generated current from incident light, the diode's leakage current, equivalent series resistance, equivalent parallel resistance, the electron charge ($1.60217646 \times 10^{-19}$ C), Boltzmann constant ($1.3806503 \times 10{-}23$ J/K), temperature of p–n junction in (K), and ideality factor of the diode, respectively.

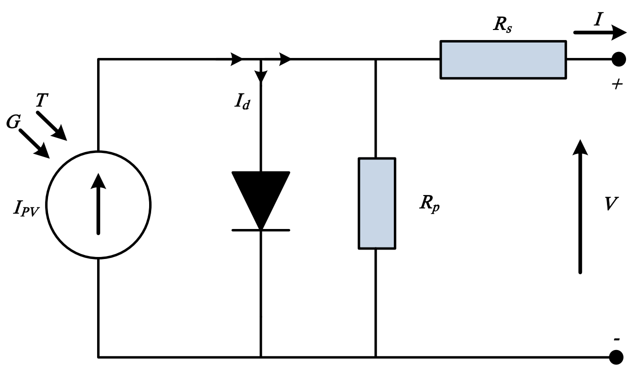

FIGURE 2. PV cell complete equivalent circuit.

The designed 500 kW PV generation system for the selected case study is consisting of 5 series PV arrays and each PV array has 330 Sun-power SPR-305-WHT-U (305W) solar panel, which composed of 5 series and 66 parallel PV cells. The boost DC/DC converter is employed to step up the output voltage of the PV array. In addition, maximum power point tracking (MPPT) controller is needed to maximize the energy efficiency of the PV output. The incremental conductance (IC) MPPT method is used in this paper due to its fast tracking response, low ripples, and high tracking accuracy [24].

C. CONTROLLING PV VOLTAGE SOURCE INVERTER

The second stage in the PV generation system is the voltage source inverter (VSI), which is utilized to feed and control the DC output power of PV into the AC utility grid. The two level VSI is selected for the selected case study due to its lower components count and its widespread in industrial PV systems. The synchronous d-q reference frame is used for implementing the VSI controller as provided in [4]. The main functionalities of the controller is to synchronize the PV generation with the utility grid in addition to controlling the active and reactive power injection into the utility grid. A phase-locked loop (PLL) system is employed to synchronize the output voltage of the VSI with the grid [25]. The detailed design method of the VSI controller can be found in [26]. The main parameters of the selected PV system in the selected case study are summarized in Table I.

TABLE 1. Parameters for PV system and its controller.

Component	*Value*
Number of cells per module	96
Open circuit voltage V_{oc}	64.2 V
Short-circuit current I_{sc}	5.96 A
Operating temperature T	25 °C
PV side capacitance C_1	400 µF
DC link capacitor C_2	70 mF
Total transformer leakage impedance [R_{xfo} L_{xfo}]	[0.002 0.06] (p.u./P_{nom})
Choke impedance [R_{chock} L_{chock}]	[2e-3 Ω 250e-6 H]
Nominal DC bus voltage of PV system	600 V
VSC switching frequency	1980 Hz
MPPT switching frequency	5 kHz
VSC rated	500 kVA
V_{DC} controller PI-1 [K_p K_i]	[7 800]
Current controllers PI-2, PI-3 [K_p K_i]	[0.3 20]

Fig. 3 shows schematic diagram of the complete PV generation system and controllers. The sensed output voltage V_{PV} and current I_{PV} of the PV array are fed to the IC MPPT method, which controls the demanded duty cycle D_t of the boost converter according to the maximum power operating point. The pulse width modulation (PWM) converts the duty cycle demand of the MPPT controller into switching signals for the power electronic switches. From another side, the controller of the VSI is implemented using the d-q reference frame transformation. The synchronization process of the VSI with the utility grid is performed using the angle θ, which is extracted using the PLL system. The DC link voltage of the inverter is sensed in order to control the injected active power into the grid.

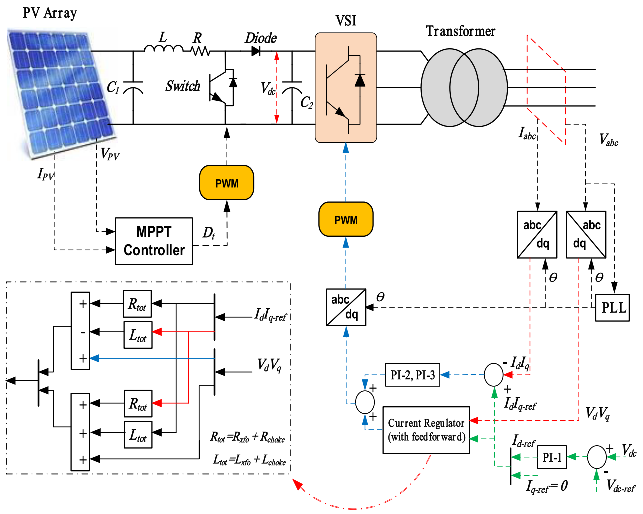

FIGURE 3. Schematic diagram of complete PV system and control scheme.

III. THE PROPOSED FLC-BASED SMES CONTROLLER

A. SMES MODEL

The SMES technologies store the energy in the form of magnetic energy. The SMES device consists of a large superconductor inductance that operates under its critical temperature in order to be in a superconducting state. The SMES components, shown in Fig. 4, include also cooling system, chopper circuit, bidirectional voltage source converter (VSC), filtering stage, and coupling transformer. The chopper circuit functions to control the charging/discharging/standby modes of operation of the SMES device. The bidirectional VSC is employed for bidirectional transfer of electrical power between the DC side of SMES and the AC side of the utility grid. Moreover, a harmonic filtering stage is utilized to reduce the undesired harmonic orders from the output waveform. The functionality of the coupling transformer is to reduce the voltage level of the PCC bus to an acceptable level for the bidirectional VSC circuit.

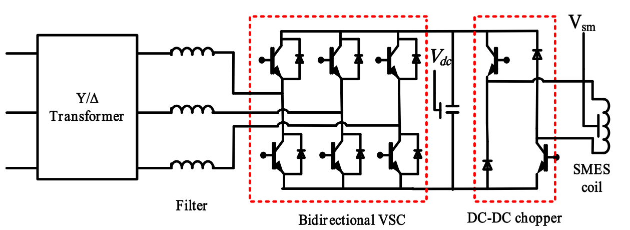

FIGURE 4. The circuit diagram of the SMES system components.

The SMES storage energy E_{sm}, the real power of SMES P_{sm}, and the average voltage of SMES coil V_{sm} can be computed based on the SMES coil inductance L_{sm}, the SMES coil current I_{sm}, the DC link voltage V_{dc}, and DC/DC chopper duty cycle D_m as in (3)-(5) as follows:

$$E_{sm} = 0.5 L_{sm} I_{sm}^2 \tag{3}$$

$$P_{sm} = V_{sm} I_{sm} \tag{4}$$

$$V_{sm} = (2D_m - 1) V_{dc} \tag{5}$$

B. THE PROPOSED SMES CONTROL METHOD

The proposed SMES controller is developed based on the fuzzy logic controller (FLC), which is considered one of the advanced control used in power system applications due to its robustness, fast response, and simple implementation. The FLC is employed for controlling the active power transfer between the VSC and the SMES coil by adjusting the duty cycle D_m of the chopper DC/DC converter circuit. Among the membership functions (MFs) of FLC methods, the Gaussian MF is used in the proposed controller for setting the input and output variables of the controller. This in turn enhances the dynamic and steady-state response of the proposed controller. Fig. 5 shows the proposed FLC method for the SMES system. There are two inputs in the proposed FLC; the first input is the difference between PV power generation and load power demand; the second input is the state of charge (SOC) of the SMES coil. Thence, smooth control of the power fluctuation due to the nature of the PV generation source. Moreover, elimination of the degraded performance of SMES due to the reliable operation of SMES by considering its SOC as an input for the proposed FLC method. The output variable of the proposed FLC is the duty cycle demand, which controls the charge/discharge active power of SMES device. Fig. 6 (a)-(c) show the input and output MFs of the proposed FLC method.

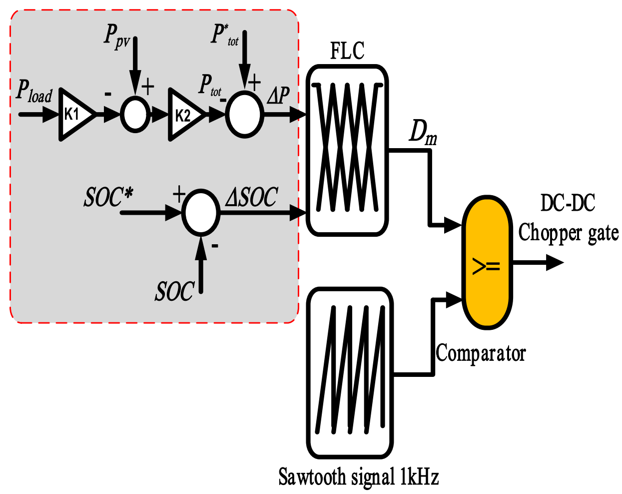

FIGURE 5. The proposed FLC method for the SMES system.

The first input of the FLC, which belongs to the power difference, and the second input for the FLC, which belongs to the SOC of SMES coil, are represented in terms of five linguistic variables such as BN (Big Negative), N (Negative), Z (Zero), P (Positive), BP (Big positive). Whereas the output duty cycle demand for the FLC is represented using the linguistic variables such as FD (Fast Discharge), D (Discharge), NO (No Action), C (Charge), and FC (Fast Charge). Table 2 shows the rule based look-up table for the proposed FLC method. Then, the implementation of If-then fuzzy rules is performed based on the rule table. Afterwards, the maximum-of-minimum composition method is employed for

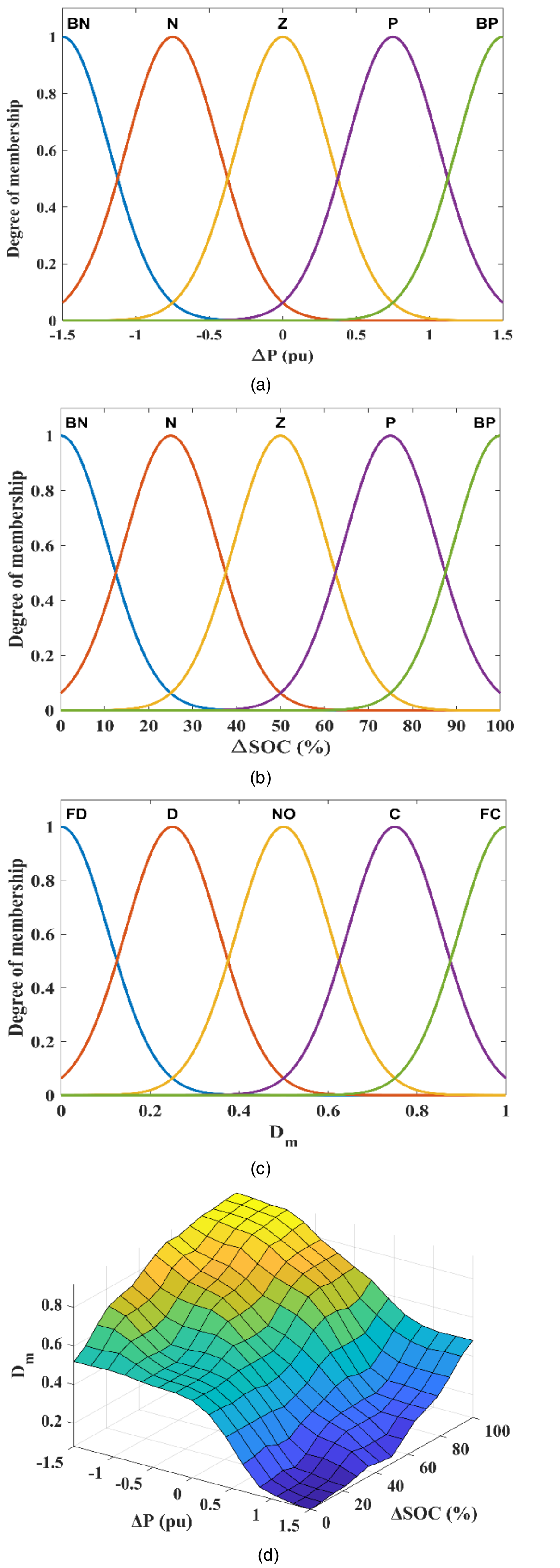

FIGURE 6. The input and output MFs of the proposed FLC method. (a) The MF of input 1(ΔP (pu)). (b) The MF of input 2 (ΔSOC (%)). (c) The MF of output (D_m), (d) The 3-D graph for duty cycle rules.

TABLE 2. Rule based lookup table for the proposed FLC method.

ΔSOC \ ΔP	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

interference stage and the center of gravity (COG) method is utilized for defuzzification process. Fig. 6 (d) shows the three-dimensional surface that represents the inputs and output MFs and the fuzzy rules in Table II for the proposed FLC. The weighting factor K_1 transfers the load active power demand into p.u., whereas the weighting factor K_2 is adjusted in order to achieve local load supply of the PV-SMES system.

C. THE VSC CONTROL METHOD

Fig. 7 shows the bidirectional VSC control for SMES system in the d-q synchronous reference frame. The PLL determines the transformation angle (θ) from the phase voltages. The angle (θ) helps to synchronize the SMES system with the AC grid in addition to transforming the measured three-phase currents into d-q currents I_d, and I_q, respectively. The controller involves direct d-axis control loop and quadrature q-axis control loop. The active power control is performed through controlling the DC link voltage V_{dc} of the converter according to be equal to the reference DC link voltage V_{dc-ref} by using the proportional-integral (PI-4) controller. The output of the controller PI-4 of DC link voltage control is the reference d-axis current I_d. Then, another proportional-integral (PI-5) controller is employed for maintaining I_d equals to its reference I_{d-ref}. The reactive power control is achieved through controlling the measured grid AC voltage V_G to be equal to the grid reference voltage V_{G-ref} through the controller PI-6. In addition, the controller PI-7 is employed for controlling the resulting q-axis current I_{q-ref} with the measured q-axis current I_q. Therefore, both the active and reactive power can be controlled for the SMES system. Table 3 includes the

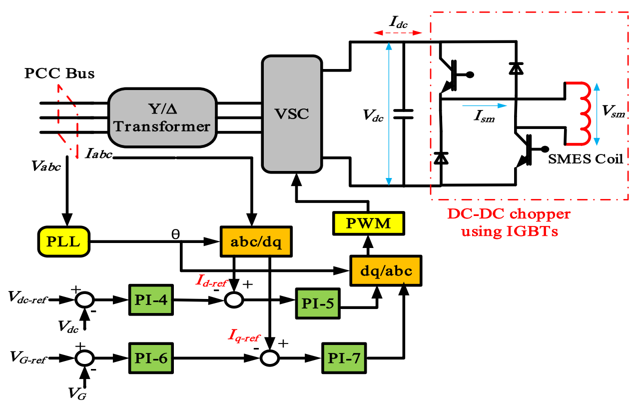

FIGURE 7. The bidirectional VSC and controller.

TABLE 3. SMES system and controller.

Component	Value	Component	Value
SMES rated current	500 A	PI-4 [K_p K_i]	[0.001 0.15]
SMES rated Energy	625 kJ	PI-5 [K_p K_i]	[0.8 200]
SMES coil inductance	5 H	PI-6 [K_p K_i]	[0.55 2500]
DC link Capacitor	5 mF	PI-7 [K_p K_i]	[0.8 200]
VSC switching frequency	1680 Hz	K_1	4.5
Chopper frequency	1 kHz	K_2	0.002

parameters of the designed SMES system and controller. The DC link voltages are selected based on the step down property of VSCs.

IV. SIMULATION RESULTS

The complete power system of the proposed case study, including PV, SMES, and loads, as shown in Fig. 1, is implemented in MATLAB Simulink environment. The simulation is carried out for a 24 hours period of the PV and loading data in order to evaluate the performance of the proposed SMES controller during all modes of operation. Fig. 8 shows the output power of PV generation and the loading profile variation of the load for one day. It can be seen that the output power of PV system fluctuates from zero output power in

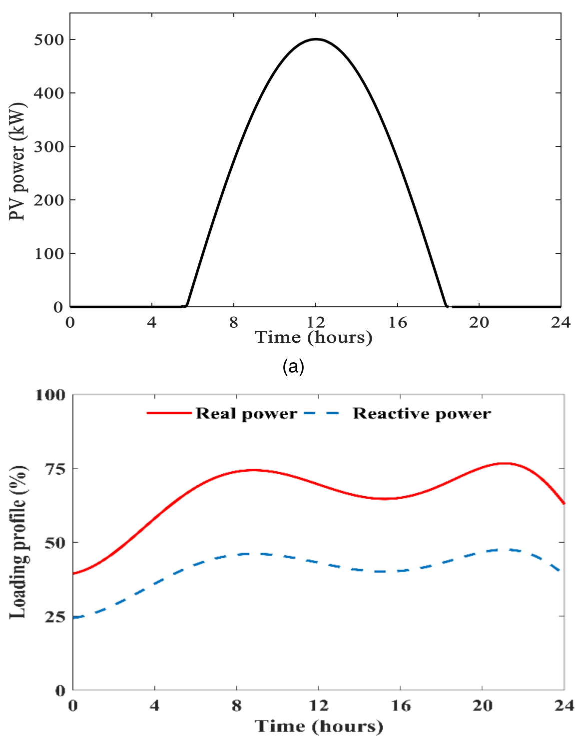

FIGURE 8. One-day data of the selected case study. (a) Profile of PV power. (b) Loading profiles.

the night to its maximum power output during the daytime. In addition, the load demands of active and reactive power fluctuate during the 24 hours profile.

The performance comparison of the active power transfer through the PCC bus is shown in Fig. 9 using the conventional PV only generation and the combined PV-SMES system with the proposed FLC method. It is clear that using the PV only requires a large amount of power transfer in the PCC bus due to the fluctuated nature of the PV generation. Whereas, using combined PV-SMES system with the proposed FLC helps to decrease the fluctuated power at the PCC bus. Thence, there is zero net power exchange at the PCC bus and the load is locally compensated from the combined PV and SMES systems. This in turn helps to improve the energy efficiency of the transmission system. Additionally, it is clear that fast response of the SMES system is obtained due to using the proposed FLC controller.

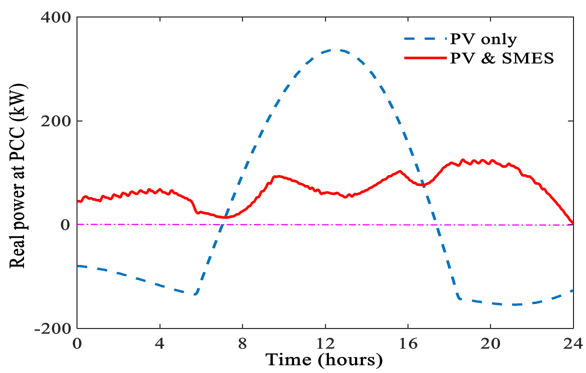

FIGURE 9. Comparison of real power exchange at PCC bus using PV only and combined PV-SMES with the proposed FLC.

Fig. 10 compares the voltage at the PCC under the conventional control method with PV only generation and under the proposed FLC with combined PV-SMES system. In the conventional PV only generation, the PCC voltage drops to 0.94 p.u. that results from the fluctuations in the load and PV generation without SMES. The proposed control method

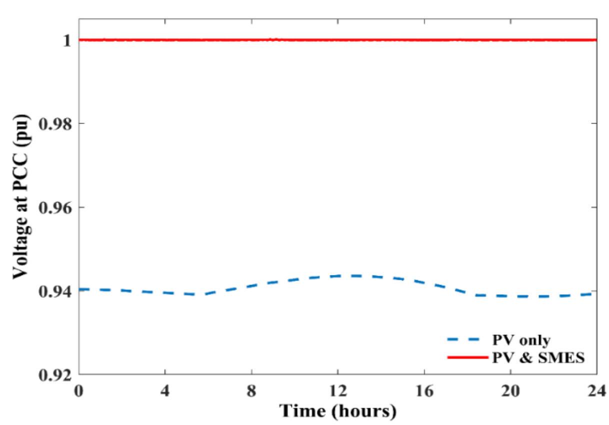

FIGURE 10. The voltage at PCC bus under conventional PV generation and the proposed system and controller.

preserves 1.0 p.u. voltage at the PCC bus during the full operating range during the 24 hrs. This is beneficial in improving the reliability and lifetime of the power system and power electronics components. The real power is absorbed/injected between the utility grid and microgrid with SMES system to preserve the reliable operation of the microgrid.

The performance of chopper DC-DC of SMES system is shown in Fig. 11 using the duty cycle of the converter and the amount of active power transferred during the case study of 24 hrs operation. In the case that the duty cycle of the chopper circuit is less than 0.5, the SMES operates in the discharge mode. Whereas, the SMES operates in charging mode by adjusting the value of duty cycle D_m to be larger than 0.5. When duty cycle equals to 0.5, the SMES operates in standby mode, wherein the energy of SMES remains constant and the real power exchange equals to zero. The active power exchange between the SMES system and the grid is shown in Fig. 11 (b). The SMES real power changes from negative to positive values between the discharging and charging mode of operation, respectively. It can be seen that smooth power transfer between the charging and discharging operation of SMES can be obtained using the proposed FLC method.

Moreover, the performance of the proposed SMES system and FLC method are evaluated at a step change in the loading and solar irradiance as shown in Fig. 12, and Fig. 13, respectively. It is clear that there is a smooth operation of the PCC voltage. The proposed controller maintains constant PCC voltage regardless of the operating point of the power system. In addition, avoidance of the DC capacitor voltage fluctuations is achieved using the proposed FLC method. This in turn preserves longer lifetime operation of the capacitor and power electronic components of the power system.

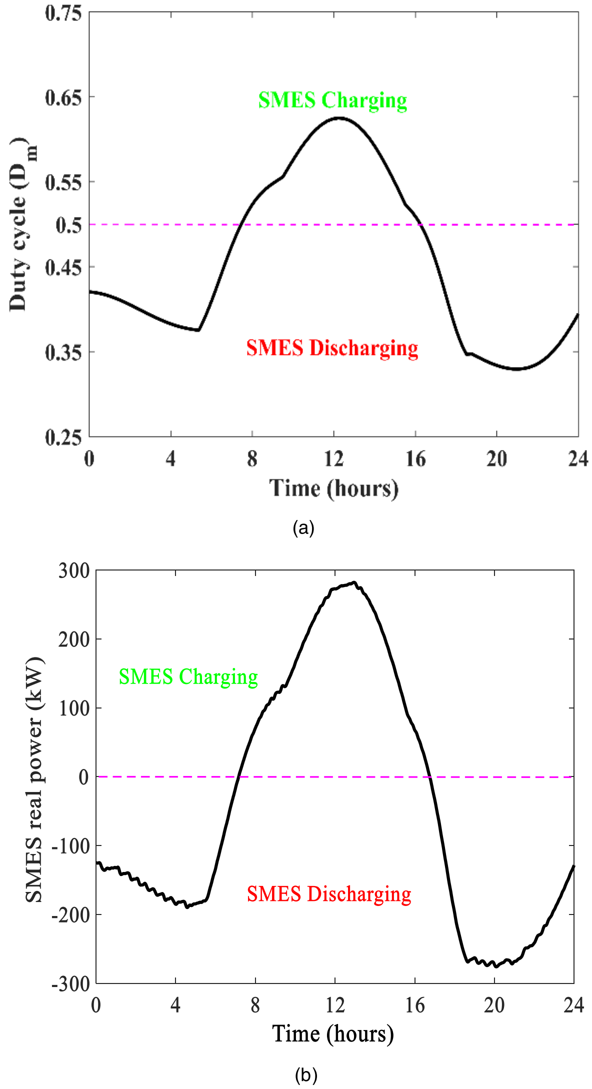

FIGURE 11. Performance of the SMES DC/DC chopper. (a) Duty cycle (D_m). (b) SMES active power.

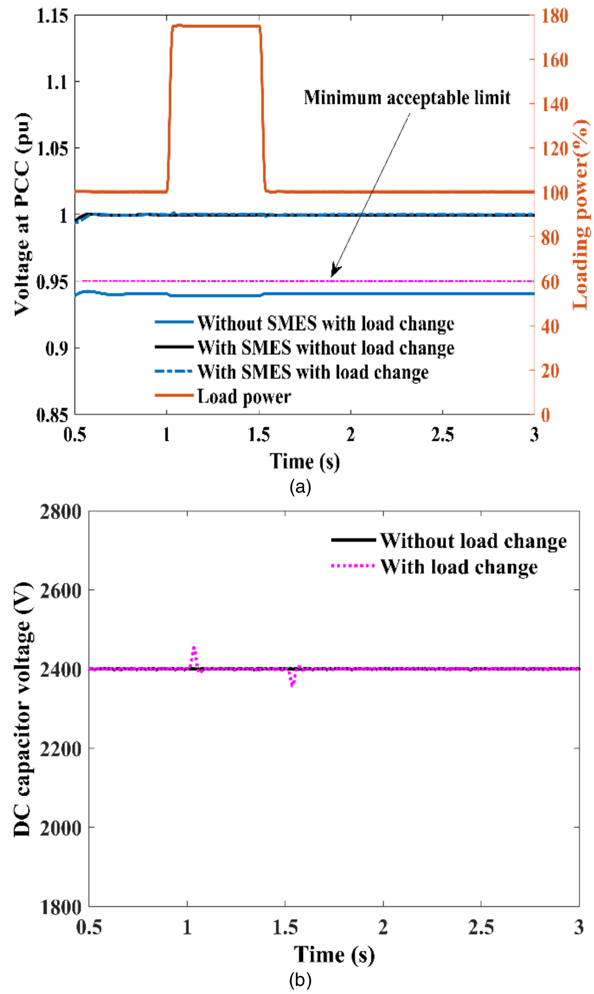

FIGURE 12. Performance of the proposed SMES system at step change in Loading. (a) Voltage at PCC. (b) DC capacitor voltage.

Fig. 14 shows the robustness evaluation of the proposed FLC method at weak utility grid systems operation. The system is tested at various transmission line lengths. It can be seen that the proposed system can preserve proper tracking

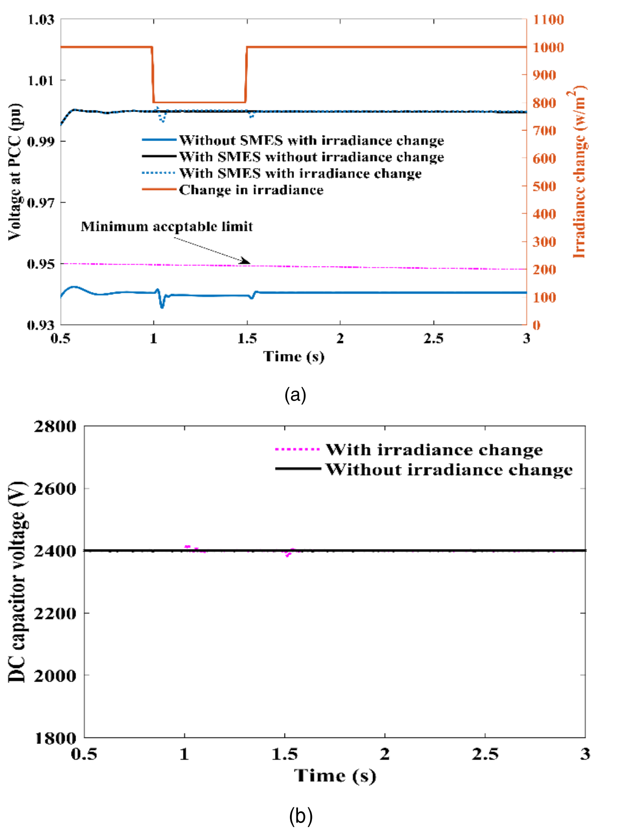

FIGURE 13. Performance of the proposed SMES system at step change in irradiance. (a) Voltage at PCC. (b) DC capacitor voltage.

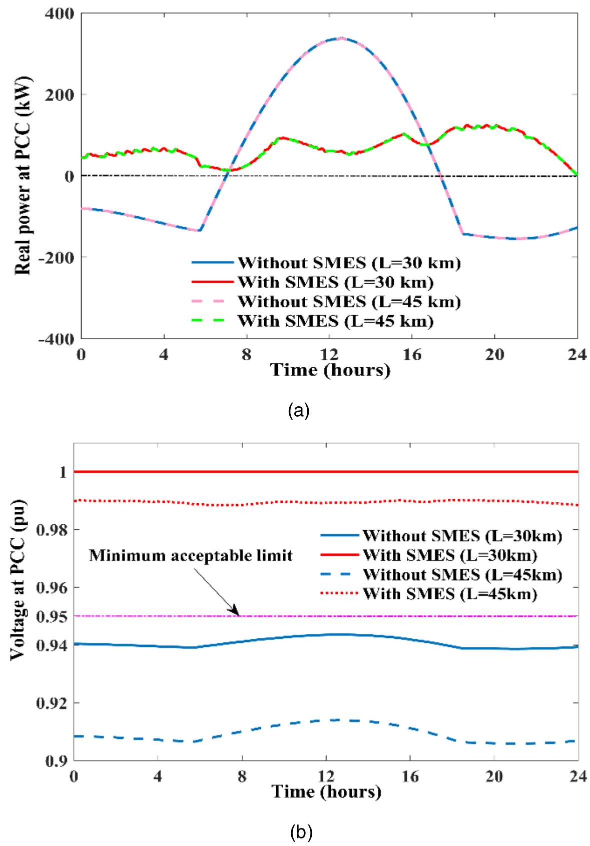

FIGURE 14. Performance of the proposed SMES system at different transmission line lengths. (a) Real power at PCC. (b) Voltage at PCC.

and control of the active and reactive powers at the PCC. Furthermore, the PCC voltage is kept within the acceptable limits for the 24-hours operation of the selected case study. Therefore, the proposed FLC method for SMES system is robust against modifications of the system transmission lines. This in turn verifies the feasibility of the proposed control method against different operating points of the power system.

From another side, the self-healing capability of the proposed microgrid has been verified by disconnecting the utility grid. Whereas, the PV-SMES system operates in the islanded mode. Fig. 15 describes the performance of the proposed SMES controller during grid disconnection (i.e., the system operates in islanded mode within a period between 1.5 to 2 sec). It is clear that the proposed SMES controller can significantly smooth the fluctuations of load active and reactive powers due to the operation in islanded mode. In addition, continuous power supply is preserved by the proposed system. Therefore, PV and SMES can completely supply the load locally without needed to the grid by applying the proposed FLC to the SMES system.

V. DISCUSSION AND COMPARISON

The proposed FLC method for the combined PV-SMES system is superior over traditional control method in improving the reliability of SMES coil, the lifetime of power components of the power electronic system, and smoothing the power fluctuation in the utility grid system. The investigations of those superiority parameters are performed as follows:

A. RELIABILITY ENHANCEMENT OF SMES

The reliability of SMES magnet is basically dependent on its current level I_{sm} and the current change rate with time $\Delta I_{sm}/\Delta t$. High levels of I_{sm} and $\Delta I_{sm}/\Delta t$ can affect the thermal margins of the magnet and sensitivity to temperature rise occurs in accordance. The proposed FLC method utilizes the SOC of the SMES magnet as an input to the Fuzzy rule set that helps to avoid high current levels of deep charge and discharge operating points. This in turn limits also the maximum change rate of SMES current $\Delta I_{sm}/\Delta t$. Therefore, double enhancement of SMES reliability is achieved by using the proposed FLC method. Fig. 16 compares the SMES current for the selected case study using the proposed FLC with the maximum charging and discharging limits in the traditional SMES current control method. It is clear that the proposed controller possesses lower values of I_{sm} and $\Delta I_{sm}/\Delta t$ for the selected case study. Thence better thermal stability and lifetime can be achieved by using the proposed control method.

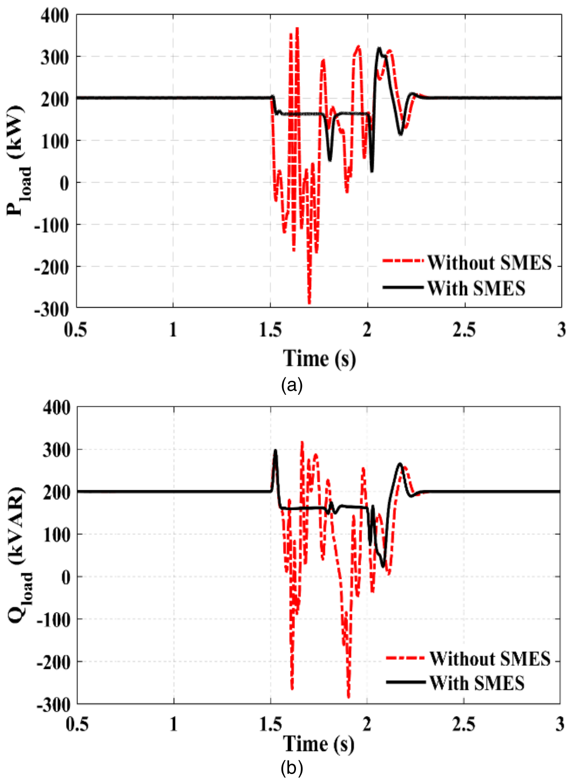

FIGURE 15. Performance of the proposed SMES system at grid disconnection event. (a) Load active power P_{load}. (b) Load reactive power Q_{load}.

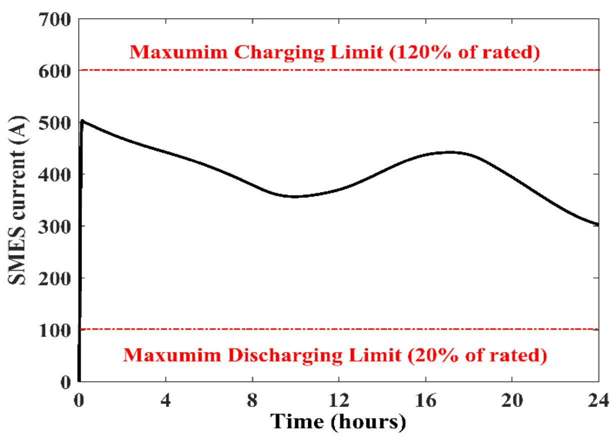

FIGURE 16. Performance of the SMES current.

B. RELIABILITY ENHANCEMENT OF SMES

The power electronic devices, including power semiconductor switches and capacitors, are the most reliability critical elements of the PV and energy storage systems [27]. The lifetime of DC link capacitors L_c can be obtained using (6) as follows [28]:

$$L_c = L_b \times \left(\frac{V_r}{V_{cap}}\right) \times 2^{\left(\frac{T_m - T_{cc}}{10}\right)} \tag{6}$$

where L_b represents the capacitor base lifetime, V_{cap} denotes to capacitor's operating voltage, V_r represents the capacitor rating voltage, T_m is the maximum value of case temperature, and T_{cc} is the operating case temperature of the capacitor. Whereas T_{cc} is dependent on the operating ambient temperature T_a, the capacitor RMS current I_{cap}, its thermal resistance $R_{th,cap}$, and its equivalent series resistance (ESR) as in (7) as follows:

$$T_{cc} = T_{cc} + I^2_{rms,cap} \times ESR \times R_{th,cap} \tag{7}$$

It is clear from (6) and (7) that the lifetime of DC link capacitor is highly affected by its operating voltage and its RMS current. Fig. 17(a) shows the lifetime change ratio (L_c/L_b) of capacitors with its operating voltage according to (6). The deep charge and discharge lead to high operating voltages of DC link capacitors. The performance of the DC link capacitor voltage under the proposed FLC controller is shown in Fig. 17(b). It can be seen that the proposed controller eliminates the high operating voltages of DC link capacitors. Therefore, the operating lifetime of power electronic components is extended and the reliability of the whole power conversion system is improved.

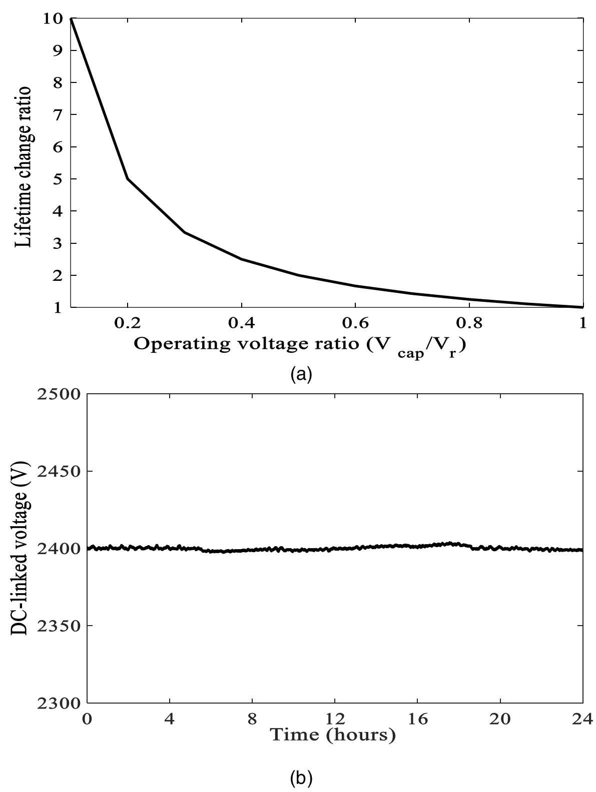

FIGURE 17. Performance of the proposed FLC method on DC link capacitors. (a) Lifetime v.s. operating voltage. (b) DC link voltages during 24 hrs case study.

C. PERFORMANCE COMPARISON

The performance parameters of the proposed FLC method have been compared with the most featured control methods in the literature in Table 4. The comparison includes the effects of the control methods on the grid system, SMES device, and the power system components. The PI control

TABLE 4. Comparison between the proposed FLC-method with the featured SMES controllers in literature.

Method	Methodology	Adaptability of power smoothing	SOC Consideration	SMES device reliability	capacitor lifetime	Complexity
Ref [19]	Model predictive control (MPC)	√	√	High	Low	Very high
Ref [20]	PI controller	×	×	Low	Low	Low
Ref [21]	Self-tuning controller	√	×	Low	Low	High
Ref [22]	Fuzzy logic controller (FLC)	√	×	Low	Low	Low
Proposed	Fuzzy logic controller with considering SOC of SMES device	√	√	High	High	Low

method in [20] lacks for adaptability of power smoothing with the fluctuated nature of PV generation and loading system. Whereas, adaptive methods preserve faster and more accurate controllability of the power fluctuations. Regarding the inputs of the controller, the method in [19] and the proposed method consider the SOC of the SMES device. This in turn provides higher SMES device reliability than the other methods. However, dependency on accurate modelling and weighting factors adjustment limits the applicability of the MPC and self-tuning control methods. Moreover, the proposed method achieves near constant DC link voltage of capacitors that makes the proposed method superior in maintaining a longer lifetime of the DC link capacitors. Whereas, traditional control methods in the literature cause voltage fluctuations over the DC link capacitors, which shorten their lifetime. Therefore, it can be concluded that the proposed FLC method is beneficial and enhances performance and reliability with the lower complexity of the combined PV-SMES system.

VI. CONCLUSION

This paper has proposed a new control method for PV-SMES systems based on fuzzy logic control (FLC). The proposed FLC method preserves higher reliability of the SMES device through considering its state of charge (SOC). In addition, the proposed controller eliminates the fluctuated nature of the PV generation through local load management. The proposed FLC method also maintains a longer lifetime of the DC link capacitors through avoiding high operating voltages due to deep charge and discharge operations. The performance and reliability of the proposed system and control method have been investigated using the selected combined PV-SMES case study in simulation platform. The fluctuated nature of the PV generation and load demands are considered in the proposed case study. Moreover, the superior performance of the proposed FLC method is verified through its performance criteria comparisons with the most prominent SMES controllers in the literature. The comparison criteria includes the impacts of applying the control method on the grid power system, the SMES device, and the power system components.

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SAYED M. SAID was born in Aswan, Egypt. He received the B.Sc. and M.Sc. degrees in electrical engineering from Aswan University, in 2006 and 2014, respectively. He is currently pursuing the Ph.D. degree with the Faculty of Electrical Engineering and Informatics, Doctoral School of Electrical Engineering, Budapest University of Technology and Economics, Budapest, Hungary. He has been a Research Assistant with the Electrical Engineering Department, Aswan University, since 2010. His research interests include power system analysis, renewable energies, power system control, wind energy with superconducting magnetic energy storage (SMES), and the integration of wind/PV based on SMES to grids.

MOKHTAR ALY (S'14–M'18) received the B.Sc. and M.Sc. degrees in electrical engineering from Aswan University, Aswan, Egypt, in 2007 and 2012, respectively, and the Ph.D. degree from the Department of Electrical Engineering, Faculty of Information Science and Electrical Engineering, Kyushu University, Japan, in 2017. In 2008, he joined the Department of Electrical Engineering, Aswan University, as an Assistant Lecturer, where he has been an Assistant Professor with the Faculty of Engineering, since 2017. He is currently a Postdoctoral Researcher with the Solar Energy Research Center (SERC-Chile), Universidad Tecnica Federico Santa Maria, Chile. His current research interests include reliability of power electronics systems, especially in renewable energy applications, multi-level inverters, fault-tolerant control, electric vehicles, and light-emitting diode (LED) lamp drivers. He is a member of the IEEE Power Electronics Society (PELS), the IEEE Industrial Electronics Society (IES), and the IEEE Power and Energy Society (PES).

BÁLINT HARTMANN was born in 1984. He received the M.Sc. degree in electrical engineering and the Ph.D. degree from the Budapest University of Technology and Economics, in 2008 and 2013, respectively, where he is currently an Associate Professor with the Department of Electric Power Engineering. He is also a part-time Research Fellow with the Centre for Energy Research, Hungarian Academy of Sciences. His current research interests include the role of energy storage in power systems, computer modeling and simulation of distribution networks, and integration of variable renewable energy sources.

ABDULLAH G. ALHARBI (S'10–M'17) received the B.Sc. degree in electronics and communications engineering from Qassim University, Saudi Arabia, in 2010, and the master's and Ph.D. degrees in electrical engineering from the University of Missouri–Kansas City, USA, in 2014 and 2017, respectively. From 2010 to 2012, he was an Electrical Engineer with Saudi Aramco Company. He is currently an Assistant Professor with the Electrical Engineering Department, Jouf University, Saudi Arabia. He has authored or coauthored over 21 journals and conference papers and one Springer book chapter. His research interests include digital IC design, memristor-based circuits, memory devices, and nanoelectronics. He is a member of the Gulf Engineering Union, the IEEE Circuits and Systems Society, the IEEE Young Professionals, the IEEE Signal Processing Society, the IEEE Instrumentation and Measurement Society Membership, the IEEE Electron Devices Society, and the ACM. He was a recipient of several awards from the Saudi Arabian Cultural Mission, USA, and the University of Missouri–Kansas City.

EMAD M. AHMED (S'08–M'12–SM'18) received the B.Sc. and M.Sc. degrees from Aswan University, Egypt, in 2001 and 2006, respectively, and the Ph.D. degree from Kyushu University, Japan, in 2012. He joined the Aswan Power Electronics Applications Research Center (APEARC), from 2012 to 2018. He is currently an Associate Professor with the Department of Electrical Engineering, Faculty of Engineering, Aswan University. Moreover, he is on a leave in the Faculty of Engineering, Jouf University, Saudi Arabia. His current research interests include applied power electronics, especially in renewable energy applications, microgrids, fault-tolerant control, and battery management systems. He is a member of the IEEE Power Electronics Society (PELS), the IEEE Industrial Electronics Society (IES), and the IEEE Power and Energy Society (PES).