Studying Impacts of Electric Vehicle Functionalities in Wind Energy-Powered Utility Grids With Energy Storage Device

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ABSTRACT Recently, electric vehicles (EVs) have proven remarkable impacts on reducing pollution and their suitability for utilizing renewable energy sources (RESs) instead of fossil fuels. The continuously increasing number of installed EVs has encouraged their employment for performing additional functionalities in utility grids. This paper provides study for the impacts of EV integration approaches on enhancing the operation of utility grids. The proposed study considers the targeted renewable energy powered utility grids with installed energy storage devices. Wind energy has been utilized as a case study for the RES with considering its stochastic characteristics and its continuous fluctuations with wind speed. Additionally, the superconducting magnetic energy storage system (SMES) device is chosen due to its promising long-life operation. The various aspects of point of common coupling (PCC) voltage fluctuations, reactive power support, leveling active power of the on-peak period, and power losses are considered in the proposed study. Moreover, fuzzy logic controller (FLC) systems have been proposed for controlling EVs and the SMES device. The energy management between the installed EVs, SMES, wind, and utility grid side is achieved through the coordination of the FLC systems. The results show that reduced peak and mean values of total power losses and line active power are obtained by the proposed coordination method. Moreover, improved profiles of the PCC voltage, reactive power support, active power leveling, and sustainable and reliable power supply are obtained by the proposed method for wide operating ranges and modes of operation.

INDEX TERMS Electric vehicles (EVs), energy management, fuzzy logic controller (FLC), renewable energy, superconducting magnetic energy storage (SMES), wind energy.

I. INTRODUCTION

IN the last decade, an exponential increase of renewable energy source (RES) installations has been achieved in utility grids to get over the various problems of traditional fossil fuel sources [1], [2]. Among the various existing RESs, wind energy represents one of the most promising directions, as a reduced cost and high power generation source [3]. Therefore, high penetration levels of wind energy systems have been found world-widely. Based on the annual energy reports, the capacity of installed RESs reached more than

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200 GW by the year 2019 [4]. In which, the global share of wind energy generations was about 19% of the total installed RESs by 2019. There are several generation types for wind energy systems, including the doubly-fed induction generator (DFIG), permanent magnet synchronous generator (PMSG), and squirrel cage induction generator (SCIG) systems [5], [6]. The SCIG wind systems have found wide applications due to their reduced cost and high reliability. In addition, SCIG systems eliminate the need for the components that require continuous maintenance, such as the brushes, exciter, and slip rings.

From another side, electric vehicles (EVs) have found worldwide market as efficient, environmentally friendly, and

means of transportation without fossil fuel requirements [7]. The fossil fuel-powered conventional transportation systems were the first choice previously, which have lead to increased demands of fossil fuel. Therefore, research and industry efforts have been directed towards new transportation systems that can be powered from another new, renewable, and clean sources [8]. In 2019, the sales of EVs have achieved an increase by more than 2.1 million cars with respect to the achieved sales in 2018, which account for about 2.6% of global car sales [9]. Meanwhile, the stock of EVs has increased to 7.2 million, which represents 1% of the global car stock in 2019. The continuous movement towards using the new technologies of electrification in various types of EVs has led to a significant expansion of their markets [10]. Thence, ambitious plans have been put by several countries for increasing share of EVs in the market, which rely on regulatory and other structural measures, including zero-emission vehicles mandates, and fuel economy standards.

However, wind energy systems have exhibited a fluctuating nature due to the dependency of the output power on the operating wind speeds [11]. Additionally, the connected loads in the utility grids are continuously subjected to changes in the demanded active/reactive power. The stochastic behavior of wind generation and demanded loads has imposed several challenges on the operation, control, and sizing of utility network components [3]. The utilization of various types of energy storage systems (ESSs) has proven efficient and vital solutions for various utility applications [12], [13]. Several incredible benefits can be obtained by employing ESSs in power systems through solving the intermittent power generation issues. Several types of ESSs have been widely used, including the electrical-based ESSs (superconducting magnetic energy storage systems (SMES), and supercapacitors), thermal-based ESSs (thermal fluid, ceramic thermal, and hot water), mechanical-based ESSs (flywheel, pumped hydro, compressed air), and chemical-based ESSs (battery and hydrogen fuel cell) [14]. Among the various existing ESSs, the SMES is widely preferred due to its fast response, which makes it feasible for responding to fast charging/discharging commands [15]. Additionally, the cooperative management between microgrids [16], resilient operation of microgrids [17], energy management systems of microgrids [18], optimal scheduling of microgrids [19], have gained wide concerns in recent research.

Additionally, the targeted high number of EVs in operation would result in additional stresses on the control and operation of electrical power systems due to the increased charging/discharging power [20]. They also represent additional stochastic system for utility grids. This in turn has made the integration of EV impacts the operation and control stage of electrical power systems [10]. The various control methods of EVs and the increased share of power system capacity can make considerable effects on the power system performance [21]. For instance, controlling the charging power and/or time can shape the demanded power in utility grids. Moreover, the resulting excess power from RESs can

used directly to feed the charging power for EVs [22]. The connected EVs can also be used as ESSs for balancing the supplied and demanded electricity, and hence a smooth integration of RESs can be ensured.

The various control functionalities of EVs in electrical power systems can result in several harmful consequences, especially from the supply reliability point-of-view [23]. The uncontrolled charging of EVs does not impose restrictions on the owner side, which may lead to serious impacts on the power systems. The return of employees to their homes between hours 5 and 8 pm happens simultaneously with the increase in power consumption by home appliances [24], [25]. This in turn leads to a large increase of the peak demanded load and its duration hours. Besides, additional power losses, voltage fluctuations, and electricity prices are expected to increase and hence decreased sustainability and reliability of the electrical networks result as consequences [26], [27]. Therefore, research concerns have been increased towards proposing intelligent control and better utilization of the various connected EVs, and ESSs in coordinated manner so as to enhance the performance of electrical power systems. Moreover, the impacts of controlled charging solutions on the on-peak load demand period are essential to be studied in details [28]. The different controlled charging and discharging of EVs can provide flexibility for the owners to discharge during on-peak periods while charging at reduced load periods. Thus, the various functionalities that can be made by EVs and the coordination between EVs and ESSs are highly important, and they represent the main objectives in this paper.

In the literature, the various types of uncontrolled charging and controlled charging techniques with lithium-ion battery-powered EV systems have been discussed in [29]. The fuzzy logic control (FLC) has been employed for wind systems to mitigate the under-voltage problems. The stochastic mixed-integer linear programming method solved by GAMS toolbox has been presented in [30] for achieving optimal rated power of integrating the controlled charging battery ESSs multi-level charging facility between controlled charging battery ESSs and wind energy generation systems. In [31], a three-level game theory based approach has been proposed for the energy management between the EVs and their charging stations. In which, the charging stations are considered independent decision maker for the energy scenarios and the system operator is also included as master decision maker. In [32], a robust optimization scheme for optimized and stable operation of EV aggregators with considering the uncertainties of market prices has been proposed.

In [33], the hull moving average and gravitational search algorithm has been proposed to smooth voltage fluctuations for studying the impacts of lithium-ion and NiMH based EVs with controlled charging and discharging. The wind and photovoltaic (PV) generation systems are utilized in the study. A comparison between the various approaches of integrating EVs in PV systems has been introduced. Additional study has been presented in [21] for studying the impacts of daily

load demands and PV generation profiles on the SMES systems. The reactive power dispatch has been achieved through improved efficiency sharing between the available inverters.

In [34], a control method has been proposed to minimize the charging cost of uncoordinated EV charging load model based on multi-objective optimization techniques in the presence of PV and battery systems. An optimal scheduling method using the stochastic model integrated with wind energy and fuel cells for microgrids with EVs has been proposed in [35]. The various effects of fast charging infrastructures for EVs in distribution systems have been discussed in [36] based on the controlled charging process without considering the RESs and ESSs. In [37], an electric vehicle-virtual power plant (EV-VPP) model has been proposed to overcome the problem of the transformer loading in addition to reducing the prices for congestion. A hierarchical control system (HCS) has been proposed in [38] with PV, battery, and flywheel to mitigate the low and high frequency fluctuations and to achieve DC voltage and power control functions.

Stimulated from the above-mentioned literature review, this paper provides a detailed study of the impacts of the integration approaches of EV systems on the operation of wind energy powered electrical power systems. Table 1 summarizes the contributions in this paper compared to exiting literature. The main contributions in this paper can be summarized as follows:

- The study of various impacts of control approaches and functionalities of EV systems on the performance of electrical power systems is presented in this paper. The various aspects of point of common coupling (PCC) voltage fluctuations, reactive power support, and power losses are considered in the proposed study.
- The stochastic characteristics and the continuous fluctuations of the wind, load demand, and EV loading profile are considered in the proposed study. The electricity prices are employed as inputs for the proposed energy management method.
- A coordinated control method based on FLC systems is proposed for EV systems with SMES for improving the peak load demand and its duration.
- Minimization of the dissipated power losses is investigated in this paper through the various functionalities that can be handled by EVs.

The remaining of the paper is organized as follows: Section II presents the modelling of the studied utility grid system. The various control methods of EVs in utility grids are presented in Section III. The proposed coordinated FLC systems for SMES and EV systems are detailed in Section IV. Section V provides the results of the simulated case study. Moreover, discussions and comparisons of the obtained results are provided. The paper is concluded in Section VI.

II. THE POWER SYSTEM STRUCTURE

There are several challenges facing the installations of wind energy systems and EVs in power systems. The coordination

and control of the various connected sources, loads, and ESSs are crucial issues for the efficient and stable operation of power systems. Proper utilization of the available sources and ESSs can lead to more efficient operation for power systems. Moreover, it can lead to more efficient and reliable operation for the other parts of the power systems, including transmission lines, transformers, circuit breakers, etc. The benefits of improved controllers can be related to technical and economic issues of the power system. The technical benefits are related to mitigating the fluctuations from the wind energy source and fluctuated electrical loads. Therefore, continuous reliable power supply can be obtained. The economic benefits are achieved through better utilization of the connected devices to the grid to perform several additional tasks. This in turn is beneficial for reducing the number and capacities of the required devices.

The simplified single line diagram representation of the considered power system in this paper is shown in Fig. 1. The considered power system includes the connected wind energy generation system, the SMES device, residential loads, and EVs. The connection of the different devices to the PCC is achieved through step-up power transformers. The coordination control systems have to read the measured output power from the connected devices and the electricity price and the other required signals related to the devices, and then generate the control commands in accordance. In addition, the reactive power has to be controlled so as to provide local supply through the connected devices. This in turn eliminates the need for absorbing reactive power from the grid that results in reducing the losses of transmission lines. Therefore, these issues and challenges have lead researchers to develop new control techniques and they will be covered through this paper.
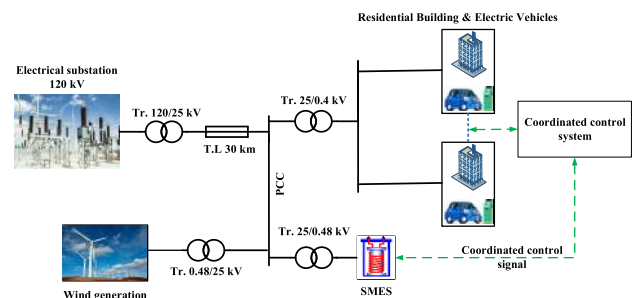
FIGURE 1. Single line diagram for the considered system with wind generation, SMES, residential loads, and EVs.

A. WIND ENERGY MODELLING

There are several types of the utilized generation system for wind energy. Each type of the generation has different power conversion structure and different affects on the reactive power injection/absorption with the grid. The SCIG type is selected in this study for representing the wind energy generation side. In wind systems, wind turbines have to be controlled to extract the available maximum power from the wind system. Whereas, the safety requirements require that if the wind speed is higher than safety limits, the output power

TABLE 1. Comparison of the contribution in this paper with featured literature review.

Reference	RESs	ESSs	Considered EV functionality	Control coordination of ESS and EVs	The main concept of methodology	Contributions
Ref [34]	PV	Battery	Controlled charging	×	Multi-objective optimization techniques	• Minimized EV charging cost
Ref [35]	Wind	Fuel Cell	Controlled charging/discharging	×	Stochastic programmable model	• Overcoming the optimal scheduling problems of microgrids with EVs
Ref [36]	–	–	Controlled charging	×	Rapid-charging DC standard (CHAdeMO)	• Reduction of energy capacities • Estimations of fast chargers infrastructures for EVs
Ref [37]	Undefined	Undefined	Controlled charging/discharging	×	Electric vehicle-virtual power plant (EV-VPP)	• Minimizing the prices for congestion • Enhance the loading of transformers
Ref [24]	Wind	–	Controlled charging/discharging	×	Adaptive dynamic programming and sliding mode control	• Provide the frequency regulation functions at various load and/or wind step changes
Ref [38]	PV	Flywheel and battery	Controlled charging/discharging	×	A hierarchical control system (HCS)	• Mitigate the low and high frequency fluctuations • DC voltage control • Power control
Proposed	Wind	SMES	Uncontrolled charging, Controlled charging, Controlled charging/discharging	✓	Coordinated fuzzy logic control system	• Study impacts of EV functionalities • Considering stochastic behavior of RESs and loads • Proposed coordinated control method between SMES and EVs • Reduced total power losses of the studied system

from the wind system is limited to its nominal value through pitch control mechanisms. The extracted output power from the wind P_{WT} can be expressed as the following [39]:

$$P_{WT} = \frac{1}{2} \rho \pi R^2 v^3 C_p(\lambda, \beta) \quad (1)$$

where, ρ, R, v, and C_p denote to air density, blade length, wind speed, and efficiency of power extraction for the wind turbine. The estimated C_p is dependent on the tip-speed ratio (TSR) λ, and pitch angle β. The TSR of wind turbines depends on blade length, wind speed, and its rotational speed. The TSR is estimated as follows:

$$\lambda = \frac{R \omega_l}{v} \quad (2)$$

where, ω_l denotes to the wind turbine rotational speed. The efficiency at the maximum power point ($C_{p,MPPT}$) is obtained for any particular TSR value (λ_{opt}). To preserve the operation at the maximum power, there is a unique speed to operate the wind turbine due to the correlation among C_p and λ. At the normal operation, pitch angle β is maintained at zero. Using (1) and (2), the extracted power from the wind turbine can be expressed as follows [39]:

$$P_{WT} = \frac{1}{2} \rho \pi R^5 \omega_l^3 \frac{C_p(\lambda)}{\lambda^3} \quad (3)$$

Whereas, the wind turbine torque is expressed as follows [39]:

$$T_{WT} = \frac{P_{WT}}{\omega_l} = K \omega_l^2 \quad (4)$$

where, K is expressed as follows:

$$K = \frac{1}{2} \rho \pi R^5 \frac{C_p(\lambda)}{\lambda^3} \quad (5)$$

At operation with optimized value for TSR, i.e. λ_{opt}, the efficiency of power extraction becomes maximum ($C_{p,max}$). Therefore, the wind turbine speed is controlled to maintain the optimum λ_{opt}.

B. SMES MODELLING
The SMES represents a promising ESS that has long lifetime, high efficiency, and fast response. This has resulted in applying SMES systems in several applications and functions in the power system. The SMES operates through storing electrical energy in magnetic energy forms. The SMES mainly includes large inductance from superconducting materials, which has to be operated under its critical temperature to be maintained in the superconductor state. The main components of the SMES power circuit are shown in Fig. 2. It can be seen that the SMES coil side is operated by a bidirectional dc-dc power converter. The control of the operating duty cycle of the converter can control the charging/discharging operation of the SMES. The second part is the dc-link capacitor side, which performs the power decoupling function between the dc side power and the ac side power. The third part is the bidirectional dc-ac power inverter. The two level converter is selected in the proposed system as a commonly utilized topology. Each phase leg has two power switches, which operate in complementary manner. The bidirectional dc-dc power inverter has to control the operating status of the SMES with
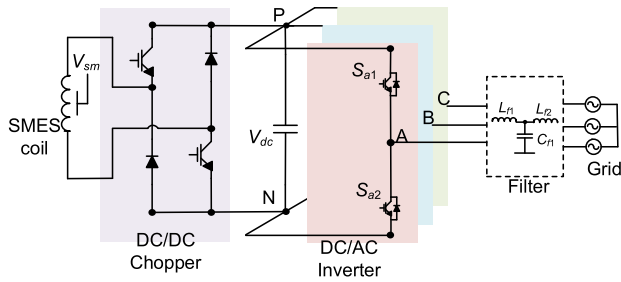
FIGURE 2. The power circuit and components of the SMES system.

the utility grid system to be in charging/discharging/standby modes. Moreover, the dc-ac power inverter can participate in controlling the reactive power flow from/to the utility grid.

The stored energy in the SMES E_{sm} is dependent on the value of the SMES inductance L_{sm} and the current of the SMES I_{sm}. It can be expressed as follows [40]:

$$E_{sm} = 0.5 \times L_{sm} \times I_{sm}^2 \tag{6}$$

In addition, the active power of SMES P_{SMES}, the voltage across the SMES V_{sm}, voltage over the dc-link V_{dc}, and the operating duty cycle D_m of the dc-dc power converter can be related as follows [40]:

$$P_{SMES} = V_{sm} \times I_{sm} \tag{7}$$

$$V_{dc} = \frac{V_{sm}}{(2D_m - 1)} \tag{8}$$

III. FUNCTIONALITIES OF EVs IN UTILITY GRIDS
With the increased numbers of EVs, they have become influencing elements in utility grid performance. The control of the charging/discharging time and type can change the generating and/or loading behavior of the grid. There are several control modes for EVs in the utility grid. The most featured ways for controlling EVs are (i) uncontrolled charging, (ii) controlled charging, and (iii) controlled charging and discharging integration approaches. In the uncontrolled charging integration approach (UCCIA), the existing EVs are connected without control from the utility grid operators. Therefore, they do not participate in additional functionalities in the utility grid system. The EV owners do not have any restrictions on charging time for EVs and they can charge them at any time. This control strategy adds several challenges and stresses to the power systems operation. Usually, owners start the charging process immediately after returning home between 5 p.m. to 8 p.m. [21]. In the same time slot, residential loads start and the loading behavior increases in accordance.

From another side, adding improved control strategies for EVs would provide better utilization for their inherent energy storage batteries. The first method is achieved through the controlled charging integration approach (CCIA). In this approach, the charging process of EVs is restricted during the on-peak loading time slot. Therefore, the loading profile of the system is improved compared to the UCCIA. This

process utilizes the recent advancements in the communication systems and the smart grid concepts and components. Another approach has been presented through the controlled charging and discharging integration approach (CC/DIA) for EVs. In this mode, the charging time of EVs is restricted in addition to the participation of the EVs in discharging for supplying the loads during the on-peak loading and/or low wind generation scenarios. Therefore, this approach enhances the utilization of the already available EV storage components to participate in the utility grid regulation and generation/loading balance. This can also eliminate the need for new installations and/or increase capacities of the required ESS in utility grids. It has become clear that EVs can take several integration approaches with utility grids with distinguished effects on the power systems performance.

The current study in this paper is based on EV models of Nissan Leaf EVs, which have Li-ion batteries with 24 kWhr capacity in each EV. It is considered in the study that the SOC for EVs in the initial state equals to 20% with efficiency of 90% with power rating of 6.6 kW. The start time of EV connections is usually modelled using the Gaussian distribution as follows:

$$f(t, \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp^{(\frac{-(t-\mu)^2}{2\sigma^2})} \tag{9}$$

Fig. 3 shows the daily profile for the connection of EVs in the selected study. The study considers a mean value for the distribution of 18, and standard deviation of 5. In the selected study, there are 8 buildings with 12 apartments in each building. Therefore, there are total of 96 apartments and setting the penetration level of EVs to 50%, and the total number of 48 EVs are supposed in the studied system.
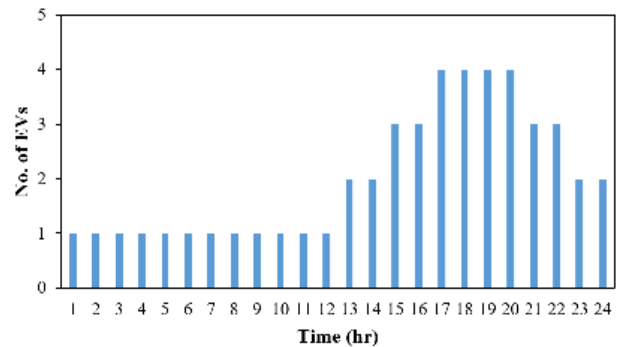

FIGURE 3. The daily profile for EV distribution in the selected case study.

IV. THE PROPOSED FLC METHODS AND THE COORDINATION ALGORITHM
In this section, three main contributions of the paper are presented, including the SMES side FLC method, the EV side FLC method, and the proposed coordination algorithm. The coordination method controls the timing and the power flow among the different connected devices in the power system based on the collected information through the communication devices. The control signals are sent to the local

SMES controller and EV controller so as to provide the different functionality in the power system. The EV controller is responsible for controlling the charging/discharging operations of the connected EVs. Whereas, the SMES controller is responsible for controlling the charging/discharging/standby modes for the SMES. The available communication infrastructures are responsible for supplying the control system with the current electricity prices and the power flow at the PCC. Therefore, possible coordination methods can be applied to provide improved technical and economical operation of the power system. Fig. 4 shows the main components and structure of the proposed controllers.
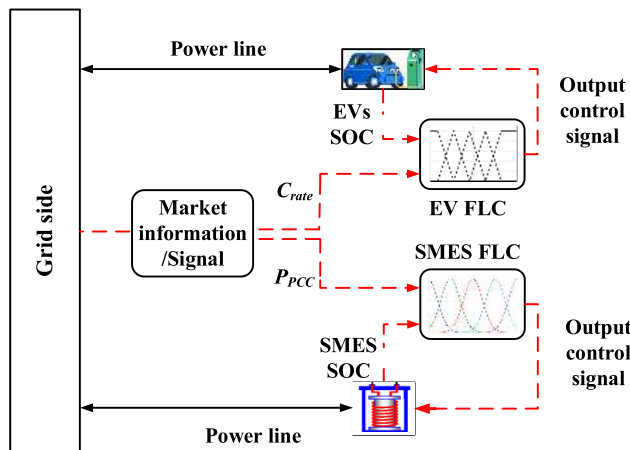

FIGURE 4. The structure and components of the proposed controllers and coordination systems.

Moreover, FLC systems have been found in several industrial applications and the market for decades. The main benefits of applying FLC systems are represented by their capability of dealing with nonlinear control systems, providing adaptive control of the system, and dealing with multiple objectives simultaneously. The concept of FLC systems is based on linguistic manners, which are similar to logical human thinking. The FLC system simulates the human reasoning capabilities. Moreover, FLC systems can handle the various constraints of the system. FLC systems are selected in this paper as smooth, simple, feasible solution with low cost microcontroller implementations, and fast control systems.

A. FLC FOR THE CONNECTED SMES

Fig. 5 shows the structure of the proposed SMES FLC system. The proposed FLC is responsible for managing the different operating modes of the SMES. The proposed controller has two different inputs and one output to control the SMES. The first input is based on the sent information about the PCC power. The connected devices to the power system at the PCC are the wind generator, the residential loads, the EVs, the SMES, and the grid supply. The connected devices have the function of the local power supply for the loads. The power difference P_{diff} is based on subtracting the load power P_l from the available wind power P_{WT}. In addition, the
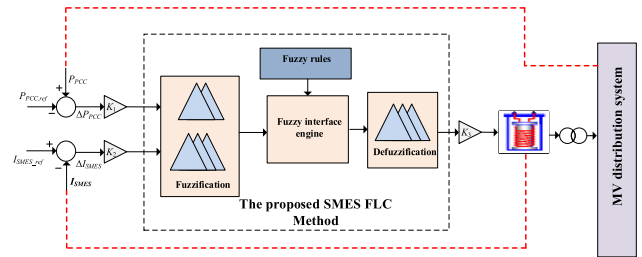

FIGURE 5. The proposed FLC for the SMES side control.

difference power P_{diff} with EV power are used to represent the PCC power. Therefore, the absorbed active power from the grid source is minimized through achieving better utilization of the available wind power and storage devices. The second input to the FLC method is the SOC of the SMES device, which is represented by the SMES current.

The FLC method normally has three main stages, including (i) the fuzzification stage, (ii) the interface engine and fuzzy rules stage, and (iii) the defuzzification stage. The fuzzification stage has the responsibility of converting the input variables of the controller into linguistic inputs that can be recognized by the FLC system. Each of the two inputs is implemented in this stage by five different levels using the Gaussian shape of membership functions (MFs). Each input is divided into five different levels, including big-positive (BPos), positive (Pos), zero (Zero), negative (Neg), and big-negative (BNeg). In the second stage, the manipulated inputs based on the MFs are evaluated with the fuzzy rules. The logic of the proposed fuzzy rules is extracted based on the different operation modes of the SMES. The duty cycle D for the bidirectional dc-dc converter has three different operating regions, which result in three different scenarios. If the duty cycle is maintained at 0.5, the SMES operates in the standby mode. In this scenario, the SMES does not contribute to the active power flow of the system. Whereas, the SMES operates in the discharging mode if the duty cycle is lower than 0.5. In the third scenario, the duty cycle is higher than 0.5 and the SMES operates in the charging mode. The third stage in the FLC is the defuzzification stage, which generates the output command based on the estimated fuzzy rules. The output is represented by five different levels, including the fast-discharge (FDCh), the discharge (DCh), the no-action (NOA), the charge (Ch), and the fast-charge (FCh) levels. Table 2 shows the fuzzy rules in the proposed FLC design.

TABLE 2. The various fuzzy rules in the proposed SMES FLC method.

Input MFs		ΔP_{PCC}				
		$BNeg$	Neg	$Zero$	Pos	$BPos$
	$BNeg$	NOA	Ch	FCh	FCh	FCh
	Neg	NOA	NOA	Ch	FCh	FCh
ΔI	$Zero$	NOA	NOA	NOA	Ch	Ch
	Pos	$FDCh$	$FDCh$	DCh	DCh	NOA
	Pos	$FDCh$	$FDCh$	$FDCh$	DCh	NOA

B. FLC FOR THE CONNECTED EVs

With the increased number of EVs in the electrical grids, proper control can maximize the benefits of their storage

devices. Based on the employed control method, EVs can participate in different functionalities in power systems using their storage devices and inverter systems. In this section, the various designs of FLC systems are presented for achieving the various operating modes and functions. Two main designs are presented based on the CCIA and the CC/DIA control methods.

There are two inputs in the designed FLC systems for EVs in this study, including the electricity price rate (C_{rate}), and the SOC of the connected EVs. According to the FLC rules and the required functionality, the connected EVs are controlled and their charging/discharging rates are determined. The input MF of the SOC is represented by five different sets that correspond to different levels of their SOC. The five levels are defined as very-small (VS), small (S), medium (M), high (H), and very-high (VH) levels. The triangular shape of MFs are used to represent the SOC input for the EV FLC method. The second input is based on the electricity price rate, and a threshold for the price is used to divide it into three main categories for the MFs. They are represented by the low price region (LPr), medium price region (MPr), and high price region (HPr). The trapezoidal shape of MFs is used to represent this input for the FLC system. The representation of the two inputs is the same for both the controlled charging approach and the controlled charging/discharging approach.

Firstly, the fuzzy rules for the CCIA are shown in Table 3. The control of EVs in this approach is achieved through representing the output of the FLC with five different control command regions. They can be classified based on the charging speed into very-low charging (VLCh), low charging (LCh), medium charging (MCh), high charging (HCh), and very-high charging (VHCh). The triangular shape of MFs is used for representing the output for the FLC method. In this approach, the connected EVs are controlled through their charging time, whereas they do not participate in supplying the electrical grid with electrical power from their storage elements. This approach motivates the EV owners to charge their EVs during off-peak loading periods and the low electricity price time slots. Thence, improved loading and control of the power system are obtained compared to the uncontrolled charging approach.

TABLE 3. The various fuzzy rules in the CCIA scenario for EVs.

Input MFs		SOC				
		VS	S	M	H	VH
C_{rate}	LPr	$VHCh$	$VHCh$	$VHCh$	HCh	HCh
	MPr	HCh	HCh	MCh	MCh	MCh
	HPr	LCh	LCh	$VLCh$	$VLCh$	$VLCh$

Secondly, the fuzzy rules for the CC/DIA are shown in Table 4. In this approach, the EVs have more participation

TABLE 4. The various fuzzy rules in the CC/DIA scenario for EVs.

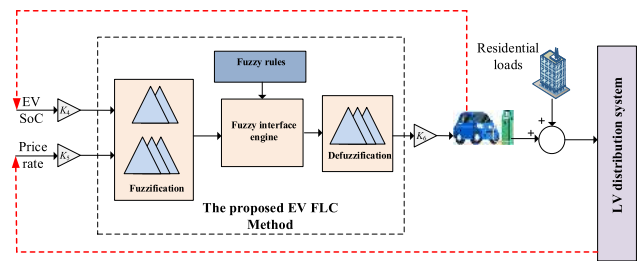| Input MFs		SOC				
		VS	S	M	H	VH
C_{rate}	LPr	HCh	HCh	LCh	LCh	LCh
	MPr	LCh	$Zero$	$Zero$	$LDCh$	$LDCh$
	HPr	LCh	$Zero$	$LDCh$	$LDCh$	$HDCh$

FIGURE 6. The FLC method for the connected EVs.

in the regulation of electrical power grids through employing their storage devices as ESS, in addition to controlling their charging times and amounts. The output of the FLC system in this approach is represented by five different sets as high charging (HCh), low charging (LCh), zero (Zero), low discharging (LDCh), and high discharging (HDCh). By applying this approach, the owners of EVs have more flexibility in charging their EVs during the off-peak loading periods and low electricity price periods. Whereas, they can discharge and sell electricity to the utility grid during the on-peak loading and the high electricity price periods. The SOC of the connected EVs is taken into consideration in the control process. The application of this approach can lead to more regulation of the electricity demand curves, controlling the on-peak loading, and having ESS reserves in utility grids. Hence, more reliable power supply can be obtained using the controlled charging/discharging approach.

C. THE PROPOSED MANAGEMENT ALGORITHM
In this section, a cooperative energy management strategy is presented for controlling the various devices in the utility grids at the PCC. Each of the connected devices can participate in improving the performance of the power system. Moreover, the coordination between the SMES and the EVs can be achieved, in addition to adding more functionalities to the EV systems. Each of the connected SMES and EVs has its local controller, which performs the regulation function of the measured voltages/currents so as to follow required references. Whereas, there is an additional central controller that manages the share of active/reactive power among the connected devices. The main objectives and priorities for the management algorithm can be summarized as follows:

- Minimizing the absorbed active and reactive electrical powers from the utility power grids so as to preserve local power supply for the residential loads.
- Operation of the connected devices in a cooperative way to mitigate the continuous fluctuations of the wind energy and the electrical loads.
- Controlling the voltage at PCC to be within the predefined limits and constraints by the utility grid operators.
- Studying various impacts of the different control approaches of EVs in utility grids.
- Achieving more economical operation for the owners of EVs to encourage them to cooperate interactively with the utility grid performance management.
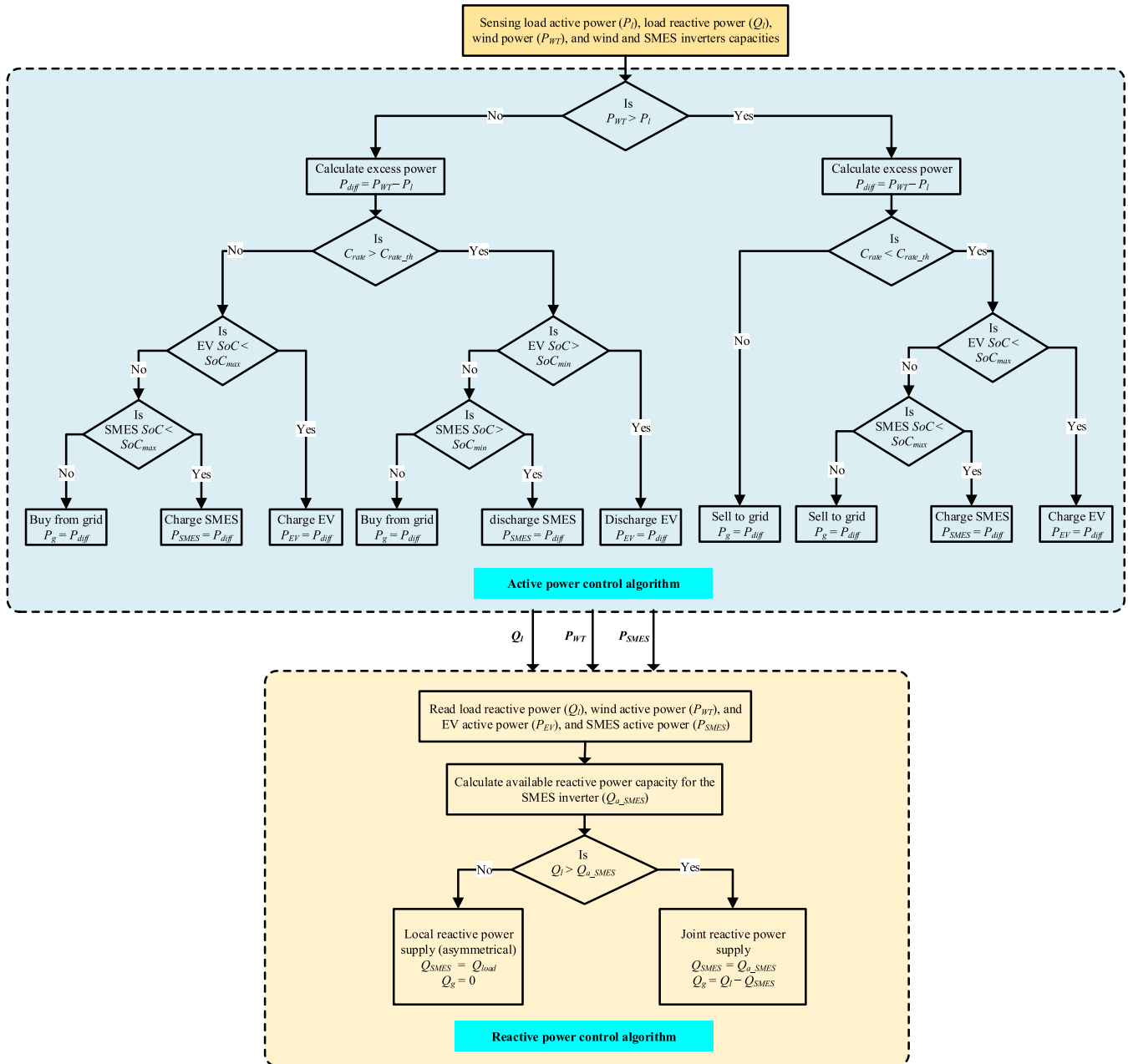
FIGURE 7. Flowchart of the proposed energy management algorithm.

- Achieving reliable power supply operation by considering the intermittent wind generated power with different loading and EV control approaches.

Fig. 7 shows the flowchart for the proposed energy management algorithm. The proposed algorithm is divided into two parts, including the active power management, and the reactive power management. The proposed algorithm is organized as follows:

Step 1: The various measured signals are collected and fed into the proposed central energy management algorithm through the available metering infrastructures. The measured parameters include: load active power P_l and load reactive

power Q_l, the connected EVs and their SOC, the SOC of the SMES, the generated wind power P_{WT}, and the voltage at the PCC.

Step 2: The control of active power flow is achieved to provide control for the loading curves, local power supply, and economical operation of EVs. When the wind power is higher than the required residential load, the extra power is utilized to charge the EVs and the SMES according to the electricity prices. A priority is given to the EV charging operation when their SOC is lower than the minimum predetermined limit until reaching the maximum limit of SOC. Then, the SMES is controlled to charge so as to absorb the extra power from

the wind generation. Therefore, reduced stresses are achieved from the electrical grids. When the EVs and the SMES reach their full charge, the extra power is sold to the utility grids to maximize the benefits from the generated wind power.

Step 3: The algorithm also controls the system when the generated wind power is lower than the required load power. When the electricity price is high and exceeds the threshold economical value, the required loading power is fed from the EVs when their SOC is higher than the minimum value. If the EVs are not charged enough, the SMES is discharged to cover the required loading power. If the SMES and EVs are not charged enough, the required active power for the load is bought from the utility grid to cover the load demand.

Step 4: If the required loading power exceeds the wind power and the electricity price is low, the EVs and the SMES are given priority to charge during the low price rate from the utility grids. Then, the required additional loading power is bought from the utility grid to benefit from the low price rate from the utility grid.

Step 5: The response of the system is determined according to the employed control approach for EVs. According to the three previously discussed control approaches for EVs, the PCC power P_{PCC} can be represented without SMES as follows:

$$P_{PCC} = \begin{cases} \pm P_g + P_{WT} - P_l - P_{EV} & \implies \text{UCCIA} \\ \pm P_g + P_{WT} - P_l - P_{EV} & \implies \text{CCIA} \\ \pm P_g + P_{WT} - P_l \pm P_{EV} & \implies \text{CC/DIA} \end{cases} \quad (10)$$

where P_g represents the grid active power at the PCC, and P_{EV} the active power absorbed/injected by EVs. Whereas, the PCC power with SMES can be expressed as follows:

$$P_{PCC} = \begin{cases} \pm P_g + P_{WT} - P_l - P_{EV} \pm P_{SMES} & \implies \text{UCCIA} \\ \pm P_g + P_{WT} - P_l - P_{EV} \pm P_{SMES} & \implies \text{CCIA} \\ \pm P_g + P_{WT} - P_l \pm P_{EV} \pm P_{SMES} & \implies \text{CC/DIA} \end{cases}$$
$$(11)$$

Step 6: Additionally, the reactive power is controlled so as to achieve a local supply from the SMES inverter as a priority. The active power of SMES and the capacity of the SMES inverter S_{SMES} are used to calculate the available possible reactive power supply from the SMES inverter. The available SMES inverter reactive power Q_{a-SMES} can be estimated as follows:

$$Q_{a-SMES} = \sqrt{S_{SMES}^2 - P_{SMES}^2} \quad (12)$$

Step 7: The load reactive power supply is locally fed from the SMES inverter when the estimated available reactive power supply from the SMES is higher than the required load reactive power. If the required load reactive power exceeds Q_{a-SMES}, then the SMES inverter supplies the load with its available reactive power supply Q_{a-SMES} and the difference is absorbed from the utility grid.

V. RESULTS AND DISCUSSIONS

The considered case study has been simulated using the MATLAB/SIMULINK program to study the different impacts of the integration approaches of EVs on the power system performance. The modelled system includes the utility grid, the SMES, EVs, a wind generator, and residential loads. The impacts of EVs are investigated with/without SMES device in the proposed study. Moreover, the proposed FLC methods for EVs and SMES are also validated. The parameters of the tested system are shown in Table. 5.

TABLE 5. The system parameters for the studied power system.

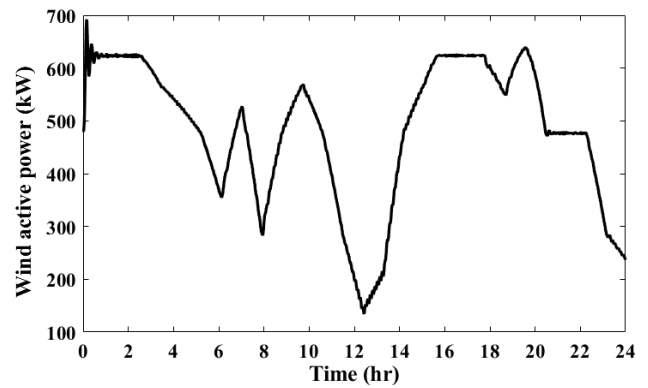| Parameter	Unit	Value
Sampling time, T_s	μs	5.0
Base line-line RMS voltage	kV	25
Wind system		
Nominal power, P_{WT}	MVA	0.5/0.9
Line voltage at wind side V_{WT}	kV 0.48	
Stator resistance and, R_s	pu	0.01965
Stator inductance, L_s	pu	0.0397
Rotor resistance and, R_r	pu	0.01909
Rotor inductance, L_r	pu	0.0397
Mutual inductance, L_m	pu	1.354
pole pairs	-	2
SMES		
SMES coil inductance, L_{SMES}	H	0.5
SMES initial current, I_{SMES}	A	3000
DC-bus reference voltage, V_{dc}	V	2400
DC-bus capacitance, C_{SMES}	mF	10

Fig. 8 shows the daily loading profiles of the studied system for 24 hours. The wind speed profile in the system is shown in Fig. 8a. It can be seen that the wind speed has continuous fluctuation during the whole day. Fig. 8b and Fig. 8c show the daily loading profiles of active and reactive power, respectively. The loading profiles fluctuate during the scenario due to customer loads. The loading has its peak value after the customers return home in the evening. Moreover, with the simultaneous existence of EVs during the night, it is important to study their impacts, and develop various integration approaches.

The behavior of daily profiles of the wind generation side is shown in Fig. 9. The generated active power from the wind is shown in Fig. 9a. It can be seen that the generated active power from the wind follows the behavior of the wind speed profile. The fluctuating output power from wind generation represents one of the most critical issues for high penetration levels of wind systems. Additionally, the reactive power profile of the wind generation is shown in Fig. 9b. The reactive power is also fluctuating during the 24 hours of the day. The daily profile of the voltage (in pu) at the wind generation terminal is shown in Fig. 9c. The fluctuations in the active and reactive power cause the fluctuation of the terminal voltage during the daily profile in the case study.
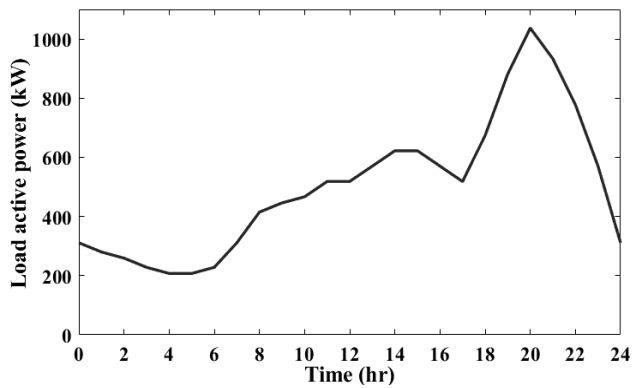
Fig. 10 shows the daily profiles for the SMES side. Fig. 10a shows the daily profiles of the active power of SMES at the different integration approaches of EVs. It can be seen that the profile of the active power is fluctuating during the 24 hrs
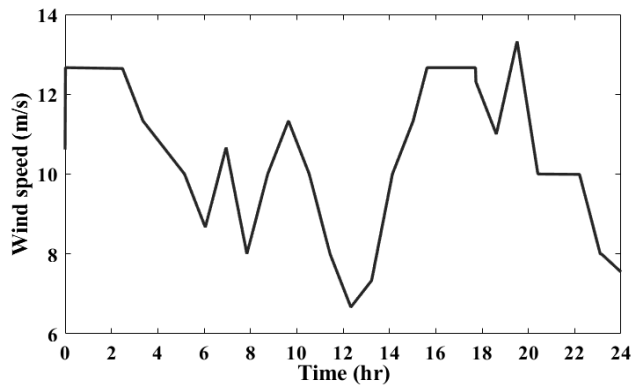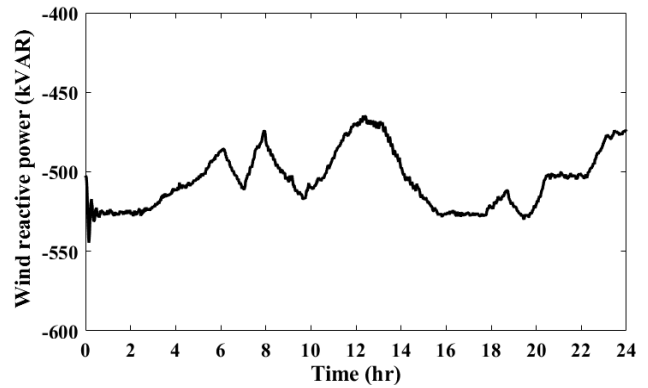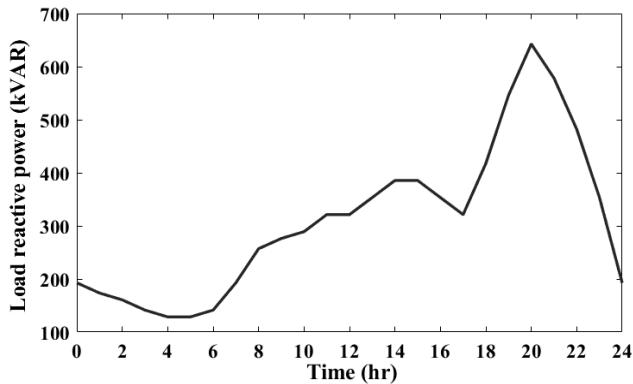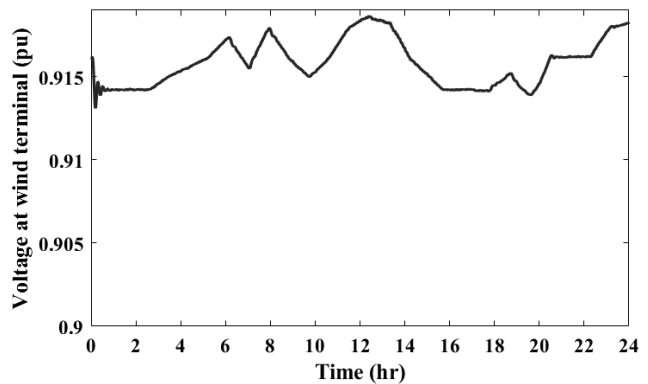
(a) The studied wind speed scenario.

(b) The studied load active power.

(c) The studied load reactive power.

FIGURE 8. The daily profiles of the studied scenarios for one day.

(a) The active power daily profile.

(b) The reactive power daily profile.


(c) The terminal voltage daily profile.

FIGURE 9. The daily profiles of the wind generation side.

with the different EV integration techniques. The profiles of the active power during the day time are the same due to the working hours. Whereas, the profiles are different during the night time due to the return of owners. The UCCIA imposes the worst behavior of the SMES output power profile due to the charging of the EVs without any control from the utility. Whereas, the CCIA improves the active power profile of the SMES compared to the UCCIA. The peak active power discharge of SMES is reduced in this approach. Whereas, the CC/DIA represents the best approach regarding the active power profile of SMES. The charging/discharging currents of SMES are controlled in this approach in addition to the reduction of the peak discharged power from SMES.

Fig. 10b shows the profile of the reactive power of the SMES inverter. It can be seen that the SMES inverter contributes to the local supply for the required load reactive power. Additionally, the various EV integration approaches possess the same profiles of the reactive power of the SMES inverter. The SMES energy and current profiles for the different integration approaches are shown in Fig. 10c, and Fig. 10d, respectively. The UCCIA approach results in the highest energy and discharging process for the SMES due to the absence of the control of the charging time/amount of EVs. It can also be seen that the CCIA improves the energy and current profiles of the SMES. This is a direct result of the control of the charging times of SMES after the owners return
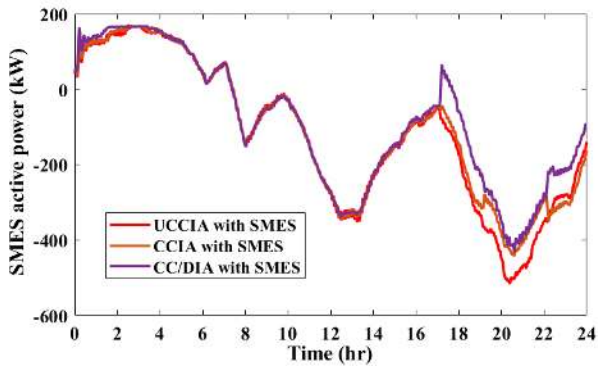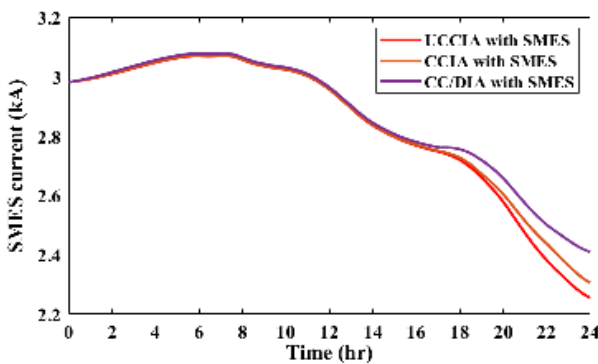
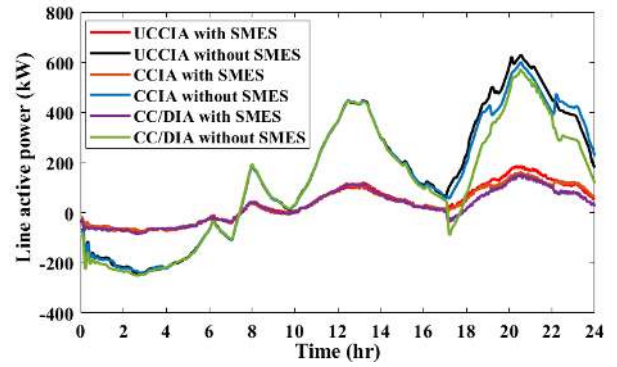(a) The SMES active power.
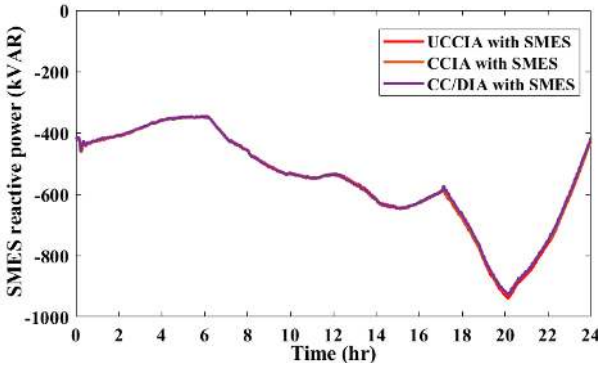
(b) The SMES inverter reactive power.
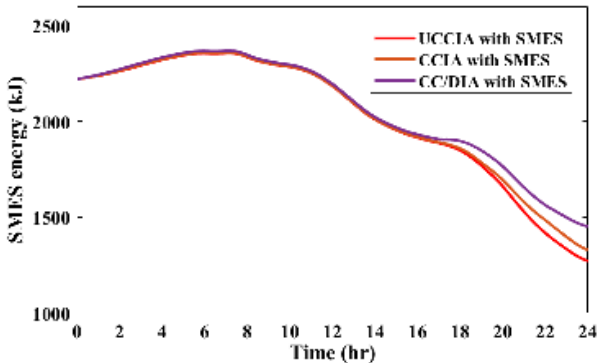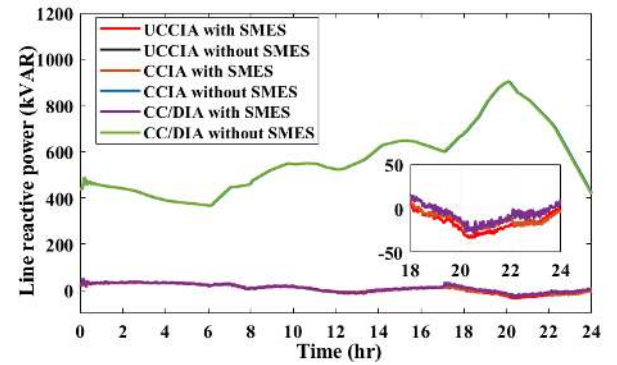

(c) The SMES current.

(d) The SMES energy.

FIGURE 10. The daily profiles of the SMES side.

(a) The line active power profiles.

(b) The line reactive power profiles.

(c) The voltage profiles at PCC.

(d) The profiles of active power losses of the line.

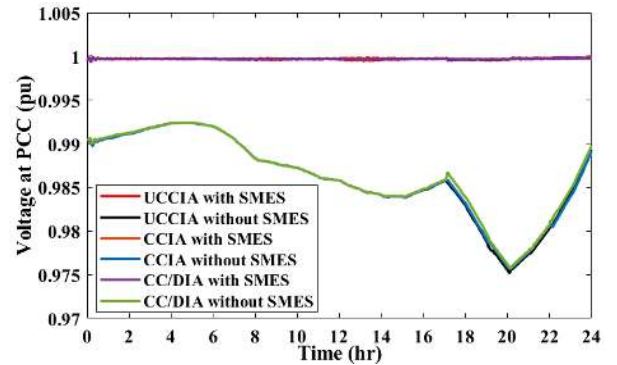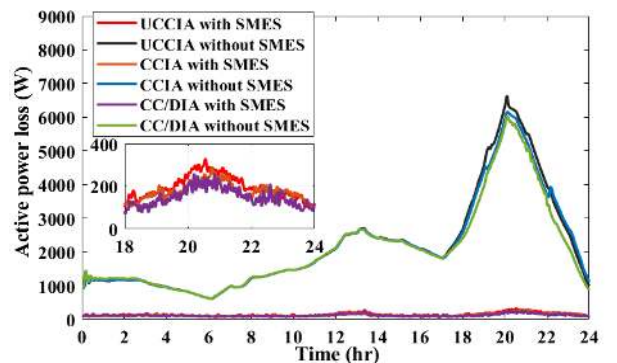**FIGURE 11.** The daily profiles at the PCC side of the different studied approaches.

home in the evening. The CC/DIA can effectively improve the profiles of the SMES energy and current due to the share of EVs in the active power control, in addition to the control of the charging times and amounts. The profiles show the improvements in the stress reduction of the SMES due to the EV integration approach.

TABLE 6. The statistical analysis of the obtained results of total power losses and the line active power.

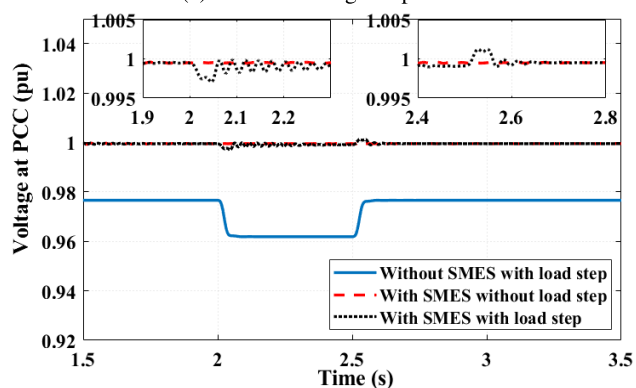|	The total power loss (W)					
Parameter	**UCCIA**	**UCCIA with SMES**	**CCIA**	**CCIA with SMES**	**CC/DIA**	**CC/DIA with SMES**
Max	6628	331.4	6154	292.7	6024	281.2
Mean	2193	134.2	2159	127.2	2081	119.6
	The line active power (kW)					
Parameter	**UCCIA**	**UCCIA with SMES**	**CCIA**	**CCIA with SMES**	**CC/DIA**	**CC/DIA with SMES**
Max	628.5	186.8	599.3	163	571.2	154.6
Mean	147.9	35.81	141	32.35	112.2	23.91
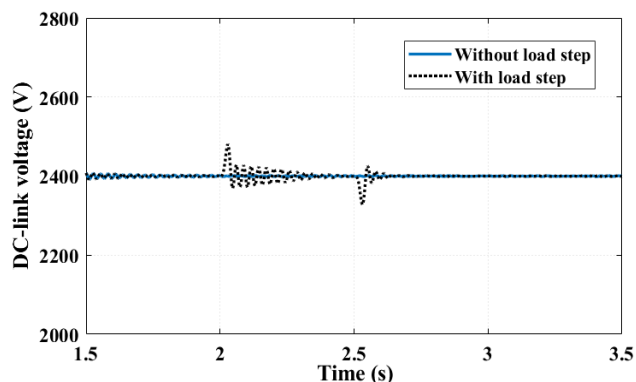
(a) DC-link voltage response.

(b) PCC voltage response.

FIGURE 12. The performance of the proposed FLC with SMES controller with load step changes.

Fig. 11 shows the daily profiles at the PCC side. Fig. 11a shows the line active power profiles for the different EV integration approaches with/without SMES. This study investigates the benefits of the cooperative coordination between SMES and EV integration approaches. It can be seen that the utilization of SMES can reduce effectively the line active power, especially during the on-peak load periods. The SMES also helps in regulating the line active power, regardless of the existence of EVs during the fluctuating wind and loads during the day time. Moreover, the utilization of various control approaches for EVs during the night period reduces the line active power at CC/DIA compared to the other methods.

Fig. 11b shows the daily profiles for the line reactive power for the EV integration approaches with/without SMES. The existence of SMES has a great influence on the line

reactive power. The SMES side inverter contributes to the local reactive power supply for the connected residential loads. However, the various EV integration approaches do not affect the reactive power performance as they do not contribute to the reactive power support. The ability of the SMES inverter to achieve local reactive power supply for the connected loads can effectively reduce the stress on the utility grid for the reactive power supply.

Fig. 11c shows the profiles of the PCC voltage for the EV integration approaches with/without SMES. It can be seen that the cooperative operation of SMES and EVs achieves a near unity pu voltage profile. The various fluctuations due to wind speed fluctuations in addition to residential and EV loads are effectively mitigated with the cooperative operation between the SMES and EVs. Moreover, the CC/DIA has little improvements compared to the other approaches in the cases without SMES due to the control of EV charging/discharging operation.

Fig. 11d depicts the active power losses at the line side for the studied approaches with/without SMES. The efficient operation of the power system is shown here with reduced line power losses by the management algorithm between the SMES and EVs. The absence of SMES leads to increased line power losses due to the absorption/injection of the active/reactive power from/to the utility grids. The local active/reactive power supply of loads using the SMES and EV integration approaches is advantageous from this point of view. The reliability of the supply power and various components is improved in accordance.

The response of the proposed FLC system is validated at step changes in the load. Fig. 12 shows the performance of the studied system with the proposed SMES based FLC method at sudden load changes. The response of the DC-link voltage of the SMES inverter with the load changes is shown in Fig. 12a. It can be seen that the proposed controller responds fast to preserve the DC-link voltage constant with the different load step changes. Fig. 12b shows the PCC voltage with the different load changes with/without SMES and with/without load changes. The proposed FLC with SMES has very small fluctuations in the PCC voltage with load step changes as shown by the zoomed-in view of the obtained results, However, the absence of SMES leads to a higher drop in the PCC voltage with load step changes. The results show the ability of the proposed controller to preserve controlled DC-link voltage of the inverter in addition to the PCC voltage at various step changes in the loads.

TABLE 7. Comparison of EV different cases with/without SMES.

Merits	Demerits	Comparison in this paper
Uncontrolled charging case without SMES		
• The usage and operation are easily achieved • No restrictions exist for grid and consumer sides • Simple algorithms are needed	• Increased loading at the on-peak period • High power loss, and voltage oscillation • High disturbances from the RESs exist due to weather variations • Increased loading of power system components, such as transmissions line, transformers, etc. • Support is essential for the power system components	• The value of the on-peak load is the highest among all the studied cases • The value of the power loss is the highest among all the studied cases • The value of the voltage oscillations is the highest among all the studied cases • No local reactive power supply is achieved • EVs is absorbing the required active power without restrictions
Uncontrolled charging case with SMES		
• The usage and operation is easy for EV owners • Supply the electrical grid with good support and auxiliary services • Reduce power loss and on-peak load period • SMES system supply reactive power • The impacts of wind fluctuations are reduced	• Information and communication systems are needed • Cooperation is required from owners of EVs • Capital cost and control complexity are high	• $P_{line,max}$ is decreased by 70.27% compared with the uncontrolled charging case without SMES unit. • $P_{loss,max}$ is decreased by 95% compared with the uncontrolled charging case without the SMES unit. • V_{PCC} at PCC is maintained around 1.0 pu compared with the uncontrolled charging case without SMES unit. • SMES injects reactive power to the electrical network. • $P_{line,mean}$ is decreased from 147.9 kW in case without using SMES to 35.81 kW in the case of using SMES. • $Ploss,mean$ is decreased from 2193 W without using SMES to 134.2 W with using SMES.
Controlled charging case without SMES		
• The usage and operation is easy • Simple algorithm implementations • The charging of EVs has barriers based on electricity price	• The on-peak load period and power loss have higher values • Voltage oscillations and disturbances due to fluctuations of RESs are high • Increased loading of power system components • It needs information and communication systems	• $-P_{line,max}$ is decreased by 4.65% compared with uncontrolled charging case • $P_{loss,max}$ is decreased by 7.15% compared with uncontrolled charging case • V_{PCC} at PCC has a little improvement compared with uncontrolled charging case • No external reactive power sources are needed
Controlled charging case with SMES		
• The usage and operation is easy for EV owners • Charging of EVs has barriers based on electricity price • Reduced power loss and on-peak load period • The SMES supplies reactive power • The impacts of wind fluctuations are reduced	• Information and communication systems are needed • Cooperation is required from owners of EVs • The capital cost and control complexity are high	• $P_{line,max}$ is decreased by 72.8% compared with the controlled charging case without using SMES unit. • $P_{loss,max}$ is decreased by 95.24% compared with the controlled charging case without using SMES unit. • V_{PCC} at PCC is maintained around 1.0 compared with the controlled charging case without SMES unit. • SMES injects reactive power to the electrical network. • $P_{line,mean}$ is decreased from 141 kW in the case without using SMES to 32.35 kW in the case of using SMES. • $P_{loss,mean}$ is decreased from 2159 W in case of without using SMES to 127.2 W in case of using SMES.
Controlled charging/discharging case without SMES		
• It presents benefits for the owners of EVs • The alleviation helps at reinforcing the electrical network • The on-peak load power and power loss are effectively reduced	• Voltage oscillations have higher values • The disturbances from the RESs are high due to weather variations • It needs information and communication systems • Cooperation is required from EV owners • Complex control and implementation are required	• $P_{line,max}$ is decreased by 9.11% compared with the uncontrolled charging case and 4.69% compared with the controlled charging case • $P_{loss,max}$ is decreased by 9.12% compared with the uncontrolled charging case and 2.11% compared with the controlled charging case. • V_{PCC} at PCC has little improvement compared with the uncontrolled charging case and controlled charging case • No external reactive power sources are required
Controlled charging/discharging case with SMES		
• Charging of EVs has barriers based on electricity price • Grid is supplied with good support and auxiliary services • Power loss and on-peak load period are extremely reduced • The SMES achieves local reactive power supply • Reduced impacts of wind fluctuations • More robust and stable grids	• It needs information and communication systems • Cooperation is required from owners of EVs • The capital cost and control complexity are high	• $P_{line,max}$ is decreased by 72.93% compared with the controlled charging/discharging case without using SMES. • $P_{loss,max}$ is decreased by 95.33% compared with the controlled charging/discharging case without using SMES. • V_{PCC} at PCC maintains 1.0 pu compared with the controlled charging/discharging case without SMES unit. • $P_{line,mean}$ is decreased from 112.2 kW in the case without using SMES to 23.91 kW in the case of using SMES. • $P_{loss,mean}$ is decreased from 2081 W without using SMES to 119.6 W with using SMES.

Additionally, statistical analysis of the various obtained results is made to evaluate the energy management and different integration methods. Table 6 shows the estimated mean and peak values for the obtained results of the total power losses and the line active power. The peak values are employed for determining the maximum loading of the system components. Ina addition, the mean value provides a reflection of the consumed energy losses in the studied system. The various analysis can be made for the other obtained results of the studied system. Table 7 shows the main merits, disadvantages, and performance comparison between the various EV integration approaches with/without SMES. In which, $P_{line,max}$, and $P_{line,mean}$ denote to the peak and mean values for the absorbed line active power, respectively. Whereas, $P_{loss,max}$, and $P_{loss,mean}$ denote to the peak and mean values for the absorbed line power losses, respectively.

It has become clear that the current study provides a straightforward mean for the decision making process for planning and developing various control methods of EVs with considering practical study of renewable energy sources and energy storage devices. The proposed analysis and obtained results are crucial for the policy makers for evaluating the status and future trends of EV integration on the power systems. This in turn can be employed for more economic, secure, and efficient operation of future smart grids. In particular, the proposed study considers the following aspects:

- The nature of the renewable energy sources and their dependency on the weather conditions.
- The wide extension of the energy storage devices in power systems.
- The increased and future installations of EVs and hence their possible contribution in power system control and management.
- The nature of the installed loads and their variability with time as active and reactive power demands.

The various criteria of electrical power systems is evaluated in accordance as following:

- The voltage fluctuations at the point of common coupling (PCC).
- The reactive power flow and the possibility of its local supply.
- The estimations of power losses due to the various integration methods of EVs.

Thence, the aforementioned considerations and the evaluated metrics are very important guiding factors for the decision-making process and the policy makers. Moreover, coordinated control of the FLC of energy storage and EVs is proposed in the paper. The various economic, reliable, and efficient operation strategies can be considered in the proposed design through defining the weights and priorities of different criteria. For instance, the priority of charging/ discharging operation and constraint limits can be considered in the proposed power management strategy. Moreover, the various integration methods and economic encouragements can be employed within the fuzzy rules in the proposed method. The various integration approaches and operating

modes are considered in the study that can be incorporated in the decision-making process.

VI. CONCLUSION
This paper presents a comprehensive study for the various impacts of different integration/control approaches of EVs on the enhancement of utility grid performance. The proposed study takes into consideration the stochastic properties of wind power generation and residential loads based on practical daily loading profiles. Moreover, the proposed study presents the effects of cooperative operation of energy storage systems with installed EVs in the utility grids. Two FLC methods are proposed in this paper for the SMES and EVs, respectively. The share of the different devices is achieved through the proposed management algorithm for supporting the local active/reactive power supply for the connected loads. Simulation results have been presented to investigate the power system performance criteria, such as the PCC voltage fluctuations, PCC reactive power flow, and transmission line power losses. The results show that the utilization of the CC/DIA, and the CCIA achieves reduction of the peak absorbed line power by 9.11%, and 4.65% compared to the UCCIA without SMES, respectively. Whereas, the peak value of the total line power losses is decreased using the CC/DIA, and the CCIA by 9.12%, and 7.15% compared to the UCCIA without SMES, respectively. While, using the SMES with the different charging methods leads to reduction of the total line power losses compared to without using SMES by 95.33% for the CC/DIA, 95.24% for the CCIA, and 95% for the UCCIA. Moreover, reduction of the peak absorbed line power by 72.93%, 72.8%, and 70.27% for the CC/DIA, CCIA, and UCCIA, respectively through using the SMES compared to without using the SMES. The proposed study represents a straightforward study that can be applied for larger power systems with different component types and numbers by extending the SMES capacity to overcome the requirements of the large test systems. This extension in the SMES energy would not affect the proposed method performance. Moreover, the recent optimization techniques can be employed for further optimizing the proposed control methods as future research extension of this paper.

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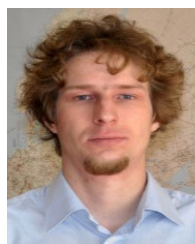
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