IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received July 8, 2020, accepted July 29, 2020, date of publication August 3, 2020, date of current version August 14, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3013762

Aggregation of EVs for Primary Frequency Control of an Industrial Microgrid by Implementing Grid Regulation & Charger Controller

SHEERAZ IQBAL[1,2], (Member, IEEE), AI XIN[1], (Member, IEEE), MISHKAT ULLAH JAN[1], MOHAMED ABDELKARIM ABDELBAKY[1,3], HASEEB UR REHMAN[1], SALMAN SALMAN[1], SYED ASAD ABBAS RIZVI[1], AND MUHAMMAD AURANGZEB[1]

[1]State Key Laboratory of Alternate Electrical Power System with Renewable Energy Source, North China Electric Power University, Beijing 102206, China
[2]Department of Electrical Engineering, The University of Azad Jammu & Kashmir, Muzaffarabad 13100, Pakistan
[3]Department of Electrical Power and Machines, Faculty of Engineering, Cairo University, Giza 12613, Egypt

Corresponding authors: Sheeraz Iqbal (engrsheeraziqbal@gmail.com) and Mohamed Abdelkarim Abdelbaky (m_abdelbaky@ncepu.edu.cn)

This work was supported by the Beijing Natural Science Foundation under Grant 3182037.

ABSTRACT After nearly a century with internal combustion engines dominating the transportation sector, it now appears that electric vehicles (EVs) are on the brink of enjoying rapid development due to numerous useful features they possess, such as less operational cost and reduced carbon emissions. EVs can act as load as well as source, by utilizing the technique known as Vehicle-to-Grid (or Grid-to-Vehicle technique if EVs are used as a load). This technique adds key features to an industrial microgrid in the form of primary frequency control and congestion management. In this paper, two controllers (grid regulation and charger controller) are proposed by considering different charging profiles, state of charge of electric vehicle batteries, and a varying number of electric vehicles in an electric vehicle fleet. These controllers provide bidirectional power flow, which can provide primary frequency control during different contingencies that an industrial microgrid may face during a 24-hour period. Simulation results prove that the proposed controllers provide reliable support in terms of frequency regulation to an industrial microgrid during contingencies. Furthermore, simulation results also depict that by adding more electric vehicles in the fleet during the vehicle-to-grid mode, the frequency of an industrial microgrid can be improved to even better levels. Different case studies in this article constitute an industrial microgrid with varied distributed energy resources (i.e. solar and wind farm), electric vehicles fleet, industrial and residential load along with diesel generator. These test cases are simulated and results are analyzed by using MATLAB/SIMULINK.

INDEX TERMS Industrial microgrid, vehicle to grid, electric vehicle, grid to vehicle, primary frequency control, state of charge.

I. INTRODUCTION

Ever-increasing energy demand, emission of carbon dioxide (CO_2), and depletion of energy resources are the leading contributors to climate change and environmental pollution across the world. This case is further worsened due to the transportation sector which accounts for more than 15% of CO_2 discharge [1], [2]. At present, with the global energy problem increasingly prominent, the renewable generation technologies have advanced rapidly [3], [4]. The introduction of power electronics, which necessitated in renewable energy sources presence, required more improvements. However, recent advancements in power electronics and batteries have paved a way for researchers to shift their focus from the internal combustion engine to electric vehicles (EVs) [5]. Electrification of the transportation sector, or as they call it ''road electrification'', promises to cater to the above-mentioned environmental issues. Energy storage systems (ESSs) and

The associate editor coordinating the review of this manuscript and approving it for publication was Chi-Seng Lam.

battery technology are key factors in the development of EVs technology and research on these technologies has shown promising results [6], [7]. In addition, the deployment of distributed energy resources (DER) has gained significant research attention to mitigate the energy crisis and the reduction of greenhouse gases [8], [9].

Advanced power systems employ microgrid which is a combination of various DERs and has control and management capabilities with well-defined boundaries. Salient features of microgrid include bidirectional power flow and autonomous nature, thus enabling them to work as a standalone entity which ensures reliability as supply to critical loads is ensured at all times. Various studies are being conducted for microgrid such as virtual power plants and autonomous grids [10], [11]. A microgrid can be classified into various types. One of them is industrial microgrid (IMG) which is formed by the interconnection of the few industrial units with renewable energy sources (RES) and ESSs [12]. The microgrid consists primarily of a distribution network of low voltage levels and connected with the power grid through a point of common coupling (PCC) [13]. State of the art microgrid has shown exciting prospects and numerous advantages but they also pose some technical challenges in successful implementation. The key challenge for the effective implementation of a microgrid is to control the supply-demand balance [14]. This difference in supply and demand is due to the interconnection of renewables in a microgrid, which works intermittently owing to their availability. Thus, EVs can be used as an alternative to solve the frequency instability problem.

Electric vehicles, when added to the power grid, can have a negative impact on the grid because of the power that they require to keep their batteries in the charged state. To overcome this negative impact, new components or already existing equipment need to be updated. However, these solutions are not feasible due to high investment. To integrate an EV in a fleet of sizeable margin in the existing power grid, the cost of upgrading and installing system equipment could reach as high as 15% [15].To overcome this problem, research is being carried out in optimal charging strategies and better designing of energy storage systems so that the addition of these large numbers of EVs is cost-effective and beneficial for utility as well as consumer [16], [17]. But, EVs can be useful to microgrid if chargers can be designed in such a way that enables bidirectional power flow between grid and ESS. There are certain advantages that EVs can provide to gird by implying optimized charging strategies. These can improve power losses and balance load-leveling profile [18]. In [19], an uninterruptable EV battery charging control is proposed, the controller operates the switches and relays in the modeled system corresponding to solar irradiation level. While, in [20], an extensive review is carried out on various methods used for wireless charging of an EV battery system. EVs can also perform reactive and active power compensation provided that proper designing voltage-source converter (VSC) be performed. The efficient switching mechanism and DC-link capacitor in VSC improves power quality as well [21]. Considering the above, considerable research has also been conducted for the efficient design of the bidirectional charger station [22], [23].

Interfacing between grid and EVs contains power electronic devices is of paramount importance that can provide bidirectional power flow. This bidirectional power flow is essential for enabling vehicle-to-grid (V2G) technology that can ensure high power quality for charging and discharging. This interfacing between EVs and utility should also take actions according to charge/discharge signals received from the utility. This timely response is necessary for grid reliability [24]. Frequency control problems in microgrid have been taken up [25], which include frequency control through charging station operator [26] and droop control [27], [28]. The role of power electronics in frequency control of industrial microgrid is presented in [29]. The charger station operator as discussed in [30] can also control primary frequency. In [31], a probability-based management strategy is proposed with continuous action space based on the deep reinforcement learning, which provides fine-grained energy management and addresses the time-varying dynamics from EVs and electrical grid simultaneously. Besides energy management, frequency regulation is also an important entity that should be taken into account for a smooth operation of the power system.

Many scholars have suggested uncertain trends of mobility for frequency regulation. Several researchers have used a novel game computational strategy to explain the relationship between aggregators and EVs in the vehicle-to-grid network model [32]. Many researchers use an autonomous distributed V2G control, whereas others use the master-slave grid control strategy for a microgrid in isolated mode. Unfortunately, master-slave control depends on vital intercommunication lines that may reduce system stability and expandability [33]. As a result, the droop control approach tends to be a better solution, but this action plan is only appropriate for fast-acting, dispatchable, electronically interfaced sources [34]. In the meantime, an adaptive neuro-fuzzy inference scheme has been developed for the generic droop controller, and some researchers have proposed a dual droop-based coordinated V2G scenario to regulate frequency deviations [35]. EVs chargers are managed to support the frequency of the grid by applying a typical fast primary frequency control (PFC) system [36]. Therefore, after the comparison of various control techniques for primary frequency control, we deduced that the grid regulation power generation controller (GRPGC) is better than other controllers. The GRPGC comprises of two controllers, the grid regulation controller (GRC) and the charger controller (CC). The response time of these controllers to industrial microgrid (IMG) is less than the aforementioned controllers. The reference signal is controlled and monitored uninterruptedly by GRPGC through a feedback mechanism. During under frequency conditions, the GRC gives quick response to stabilize the IMG through EV's battery discharging. Similarly, for over frequency conditions, the

CC immediately responds to the industrial microgrid operator (IMGO) signal, and EV's battery starts charging to control the frequency of the system.

This paper deals with devising an accurate charging strategy through the implementation of grid regulation and charger controllers. The grid regulation controller provides frequency regulation during disturbances in an industrial microgrid; while, the charger controller controls the charging process in an optimized way. Different charging profiles of EVs are considered, and based on SOC of charging profile state estimation in percentage is calculated, which determines whether the particular EV is in charging mode or regulation (discharging) mode. These controllers ensure bidirectional power flow, which controls the primary frequency of an industrial microgrid. Charging stations are designed in such a way that EVs batteries charge can be controlled when they are connected to the industrial microgrid; and in the meantime, it also provides voltage and frequency support during the various grid disturbances faced by industrial microgrid during the day.

The paper is arranged as follows: In section II, the preliminaries of the V2G framework are given. In section III, the proposed mechanism for controllers is presented. The proposed model and simulation parameters are discussed in section IV. Various events that an IMG may face during the 24-hour period are simulated and the frequency deviations during these events are studied in results and discussion section V. These disturbances include major output reduction of PV farm, tripping of the wind farm, and starting of a synchronous machine. Conclusions are presented in section VI, which depicts that by employing a bidirectional charging strategy through grid regulation and charger controllers, frequency deviations can be reduced to a significant margin. A test case is implemented and studied using MATLAB/SIMULINK software.

II. INDUSTRIAL MICROGRID AND ITS COMPONENTS

The distributed grid is an electricity system that links directly to the distribution system at a different location, or to the consumer side in order to meet the power demand of the network. The capacity of distributed energy resources (DERs) which are connected to the IMG is relatively low compared to the traditional grid. They are, thus, defined as the micro-sources. The micro sources are categorized in keeping with the operational technology of controllable generators, unmanageable generators, and energy storage systems. A few common types of micro-sources are PV systems, wind power, EVs, and diesel generators (DGs).

Fig.1 illustrates the single line diagram of industrial microgrid under consideration. The proposed model has a central AC/DC voltage source converter (VSC) and a chain of individual DC/DC converters in a parallel configuration. These Buck-Boost DC/DC converters are connected to the common DC bus which in turn, is controlled by the central rectifier station. By proper controlling of AC/DC VSC station, power can be transferred to the grid which can contribute to frequency regulation.

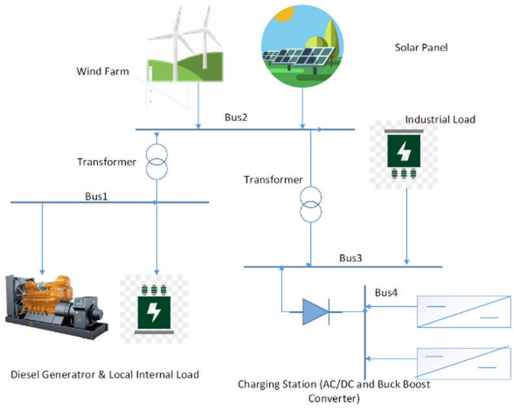

FIGURE 1. Conceptual view of an industrial microgrid.

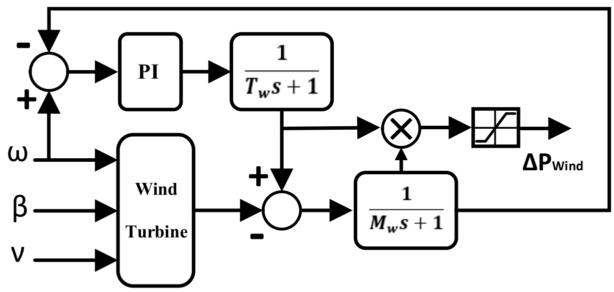

FIGURE 2. The wind turbine model.

A. MICROGRID SUBSYSTEMS

1) WIND FARM

In the construction of the wind turbine (WT) model, two significant parameters are considered: the wind speed at the precise position and the power curve of the WT. The model of the optimization of the WT which is used to measure the output power of the wind turbine generator as a function of wind speed, air pressure, catching area or spread area, and the efficiency factor as shown in Fig. 2 [27]. This power can be determined by reference to the optimization of the WT.

$$P_w = \begin{cases} 0 & v < v_{ci} \\ 0.5.sa.v^3.\rho.cf & v_{ci} \le v \le v_{co} \\ P_{wr} & v_{co} \le v \le v_{cco} \\ 0 & v_{co} < v \end{cases} \tag{1}$$

$$\begin{aligned} Sweptarea\,(sa) &= \pi\left(\frac{rm}{2}\right)^2 \\ \text{Cut on speed } v_{ci} &= 3m/s \\ \text{Corner speed } v_{co} &= 14m/s \\ \text{Cut out speed } v_{cco} &= 25m/s \end{aligned} \tag{2}$$

where rm is the rotor diameter which is taken $10m$; The density air (ρ)= $0.1kg/m^3$; Capacity Factor (cf) is the real output to the expected output ratio.

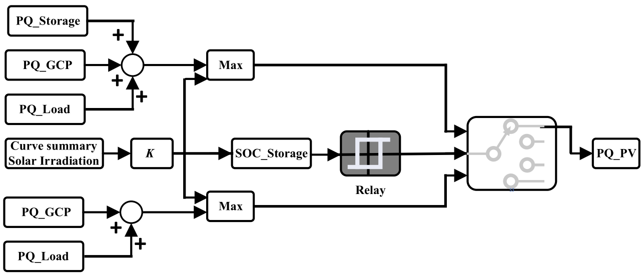

FIGURE 3. The photovoltaic (PV) model.

2) PV FARM

The energy produced by the photovoltaic (PV) farm depends upon the basis of the covered area of the panels and the amount of irradiance produced. The current output of the solar cell is directly proportional to the light that falls on the cell. Weather data (the irradiance and temperature) is used as the input parameters to determine the current, voltage, and power as an output factor. The Simulink model of PV is as shown in Fig. 3. The total current of a solar cell, which is also the difference between the diode current and the photo-current, is described in the following:

$$I_{PV} = I_l - I_{os}\left(e^{\frac{q(v+IR_s)}{nKT}} - 1\right) - \frac{V + IR_s}{R_{sh}} \tag{3}$$

$$I_L = \frac{G}{100}\left[I_{SCR} + K_1 (T - 25)\right] \tag{4}$$

$$I_{os} = I_{or}\left(\frac{T}{T_r}\right)^{\frac{3}{n}} e^{\frac{qE_{GO}}{nk\left(\frac{1}{T} - \frac{1}{T_1}\right)}} \tag{5}$$

$$I_{or} = \frac{I_{SC}(T)}{\left(e^{\frac{q(V_{OC}(t))}{nkT_1}} - 1\right)} \tag{6}$$

The total output capacity of the PV cell depends primarily on the number of solar cells added to the system. A PV system output is normally connected to the MG using an inverter to transform the DC output power on the PV system side to AC power on the microgrid part.

3) DIESEL GENERATOR

Diesel generator may be used as a standby/backup power source to resolve the problems associated with the unreliable and unpredictable existence of the RESs. The key features associated with diesel generator are the amount of electrical energy produced by DG, its working cycle, its fuel efficiency, and its fuel curve, which indicates the features of the fuel in comparison to the overall electrical energy produced.

4) ELECTRIC VEHICLES

The electric vehicle (EV) battery storage system is a power source unit that has bi-directional power flow properties. Therefore, the EVs have a great potential to provide power to the industrial microgrid to stabilize the microgrid frequency during peak hours under the guidance of an intelligent controller. The Simulink model of EV is as shown in Fig. 4 [27].

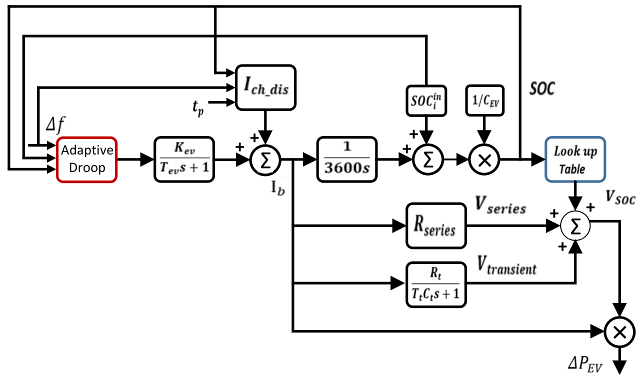

FIGURE 4. The electric vehicle (EV) model.

The EVs play two functions, i.e. when they are plugged into an industrial microgrid then the EVs will act as loads and they absorb charge. Secondly, they can also be used as storage units to provide power to the load, to meet the system's required demand and provide auxiliary services for primary and secondary frequency control. The instantaneous charging state of the EVs battery is described as follows:

$$P_{EV}^{t} = P_{EV}^{max}\left(1 - e^{\frac{at}{t_{max}}}\right) + P_{EV}^{c}, \tag{7}$$

where P_{EV}^{c} is the current status of the battery system, P_{EV}^{max} is the maximum power capacity of EV, t_{max} is the maximum charging time.

Similarly, the discharging status of the battery system of EV is expressed as:

$$P_{EV}^{t} = P_{EV}^{c}.e^{\left(\frac{at}{t_{max}}\right)} \tag{8}$$

B. STATE-OF-THE-ART V2G NETWORK

Vehicle to grid (V2G) concept is beneficial for EVs owners and addresses the stability issues of an industrial microgrid (IMG). The basic philosophy is to use EVs batteries as an intermediate source. During peak hours EVs power (active and reactive) is injected into the grid. During off-peak hours, due to minimum load demand surplus power is utilized to charge the EVs. This technology is very beneficial, for both the IMG and consumers. As the EVs owners can not only charge their vehicles by paying less cost, also they can sell power to IMG during peak hours. From power grids perspectives it is beneficial, as no additional operational cost is paid for adding additional power plants in order to supply additional power during peak demand hours due to the implementation of V2G technology.

This model requires a charging station setup, where EVs are to be plugged in for charging their batteries that can be called a charging station. Power from IMG through charging stations will be provided to EVs upon their requirement. During high load demand, power will be provided back to the grid through the charging station. The V2G framework is shown in Fig.5.

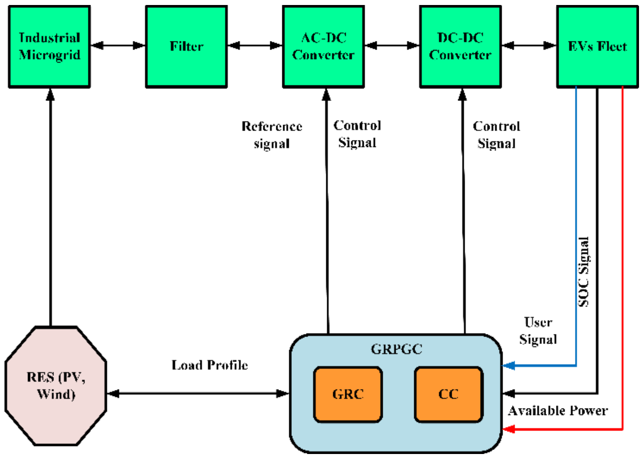

FIGURE 5. V2G framework for an industrial microgrid.

III. MECHANISM FOR PROPOSED CONTROLLERS

The two control mechanisms discussed and implemented in this study are grid regulation controller (GRC) and charge controller (CC) which are collectively named as grid regulation power generation controller (GRPGC). The GRC controls the operation of the AC-DC converter connected with the industrial grid during under frequency scenario by regulation mode (discharging mode) upon tripping of any one source or taken any heavy industrial load into service. Charge Controller (CC) control the power, during over frequency condition, upon insertion of source back into service or in load rejection or during surplus power in the grid. The grid regulation power generation controller serves as the aggregator in V2G and G2V scenarios by taking services from these two controllers. Grid regulation power generation controller facilitates owners of EVs for charging the EVs batteries upon their desire. Simultaneously, it receives signals from industrial microgrid to adjust their charging schedule and to fulfill load demand and hence play its role in industrial microgrid's smooth operation.

Two control strategies are employed in this study to implement V2G technology and to regulate power flow between EVs and the industrial grid. One controller is dedicated for controlling the switching of AC-DC converter to provide active power for charging EVs and work particularly during over frequency scenario and is named as charging controller (CC). The second controller is a grid regulation controller (GRC) that is supplying active and reactive power to grid and work particularly during under frequency conditions. The proposed architecture is shown in Fig.6.

In Fig. 6 the flow chart of the proposed strategy is presented. Initially, the monitoring of the industrial microgrid is performed through meters, then the system checks whether V2G mode is activated or G2V mode is activated. If V2G mode is deactivated and any there occurs a fault in the system, then this disturbance has to be eliminated by the existing resources in microgrid without any frequency regulation, which may unbalance the microgrid. On the other hand,

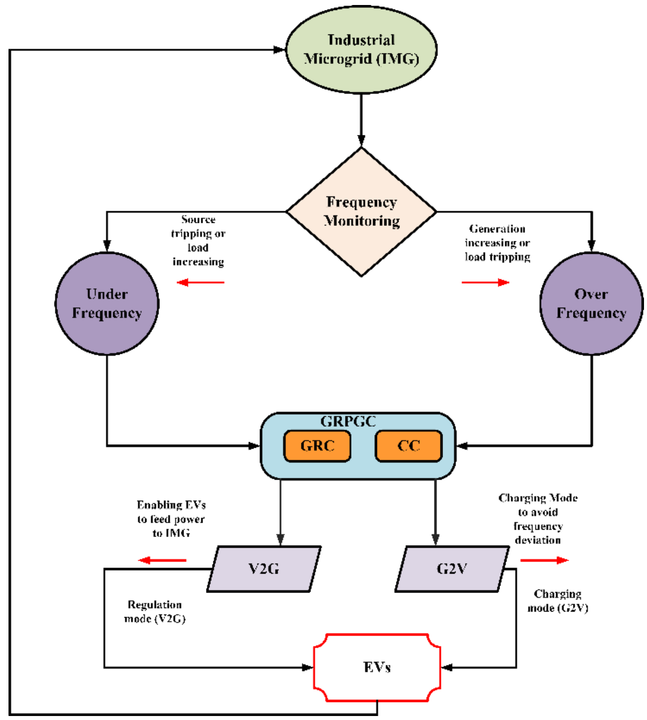

FIGURE 6. The conceptual overview of the proposed system.

if V2G mode is active, then it checks the SOC initialization, plugin state of EVs and predicts the current SOC of the battery. Based on SOC, the mode of EVs is decided whether cars are in regulation mode (discharging mode) or charging mode. If no outage or disturbance occurs, then the microgrid provides power to EVs and it acts as a load. If there occurs a disturbance in the grid, then EVs helps to maintain the frequency stability.

A. GRID REGULATION POWER GENERATION CONTROLLER (GRPGC)

The grid regulation power generation controller (GRPGC) acts as an aggregator in this V2G model. It has a direct connection with a controlled current source and also makes interaction with industrial microgrid operators (IMGO) to make a decision of EVs batteries charging or discharging. In addition, the GRPGC makes interaction with IMG's reactive power demand received by GRPGC, and as a response, it generates a signal for GRC in order to provide reactive power to the IMG.

Grid regulation power generation controller makes interaction with IMGO in order to get forecasted power demand, so that charging/discharging may be scheduled. Besides, it also has EVs charging profiles of the region/area for further facilitation of the scheduling process. By making communication with both IMGO and with EVs fleet, GRPGC makes a schedule based on EVs battery's power requirement for charging and available power to support V2G operation.

Grid regulation power generation controller having three input signals act on an algorithm according to some pre-defined criterion, based on available EVs and IMG power profile, for manipulation of these three input signals to execute G2V or V2G operation. Three input signals of GRPGC are IMG load profile signal, user signal, and EVs available SOC, respectively that decide to execute G2V and V2G mode. GRPGC input signals information is elaborated below:

1) USER SIGNAL

The consumer feedback decides the preference of G2V or V2G mode whether to charge EVs or supply active power to the industrial microgrid. In the GRPGC algorithm, the highest priority is given to the user input signal, to decide whether EVs can be used for discharging to compensate for the peak load of IMG or not. If EVs owner is willing to charge EVs, regardless of load condition of IMG, EV charger will not be in a position for the provision of active power to the microgrid. However, IMG must be allowed to provide active power during the idle state of the EVs charger based on the SOC of the battery upon the agreement between IMGO and the owners of the EVs.

2) INDUSTRIAL MICROGRID LOAD PROFILE SIGNAL

The average data of the load profile is provided by the Grid regulation power generation controller (GRPGC). The load profile is analyzed by GRPGC and the required active power of EVs batteries is calculated for IMG support. GRPGC then determines the idle state time during the day when they can provide active power. At the same time, the IMG load and the total load time of the day are calculated so that the charging schedule can be formulated and planned for charging the EVs at those hours. The reactive power demand signal is also provided by GRPGC. On the basis of the GRPGC provision, the necessary IMG reactive power is provided using the DC-link of AC-DC converter.

3) STATE OF CHARGE

The SOC is essentially identical to that of the fuel gauge for the battery pack in EVs. It is the third but most vital GRPGC input for V2G and G2V operation.

SOC determines the requirement of charging current for EVs charging. Charging current is a function of SOC. For example, if SOC of the battery shows 20%, it means there is an urgent requirement of charging batteries, and higher current and quick charging is required in minimum time. Similarly, 80% SOC indicates less charging current requirement and zero current requirement for 100% SOC. The state of charge is not only important for G2V operation but it is equally important for V2G mode as well. Agreements are charted from the SOC perspective, in which the SOC level is defined for V2G and G2V operation and agreed on a particular percentage above which batteries can be used. For example, 40% or above SOC means that agreement says that EVs batteries can only be used in V2G mode.

In case SOC is less than 40%, V2G mode will not be permitted by GRPGC. Therefore, SOC is an important input signal for GRPGC for G2V as well as V2G operation. The three input signals that have been mentioned above determine the GRPGC mode of operation, as established. However, data that has been received by using three input signals required to be manipulated so as to perform G2V and V2G operation. GRPGC for this purpose employs an algorithm in order to support this operation.

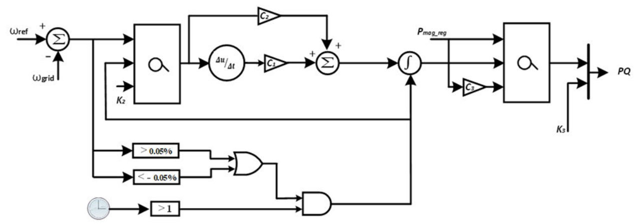

FIGURE 7. Control system for GRC.

B. GRID REGULATION CONTROLLER (GRC)

The main objective of the grid regulation controller is to support industrial microgrid during the tripping of any source and major load addition to the industrial microgrid. The grid regulation controller (GRC) provides reactive power support whenever an industrial microgrid operator request.

Grid regulation controller supplies reactive power to industrial microgrid by injection of reactive power at the point of that coupling. An industrial microgrid can request reactive power support any time and GRC is bound for immediate response through adjustment of current.

In order for effective grid regulation, frequency measurement referred to as grid frequency, is necessary. Comparing grid frequency with a reference frequency gives us deviations in system frequency. Fig. 7 shows a detailed block diagram of the controller and significant blocks/ inputs in this controller are as follows:

- A derivative has been designed so that abrupt changes in frequencies can be minimized.
- C1 and C2 are the open-loop gains that come into play when frequency deviations are within range. Changing C1 and C2 have a direct influence on the state of charge of batteries during.

C. CHARGE CONTROLLER (CC)

The charge controller plays its role when there is surplus power in the grid or over frequency condition as well as during rejection of major industrial load or restoration of a source back to the grid. With the coordination of GRPGC, it helps the industrial microgrid to avoid over frequency condition.

To charge the EVs during charging mode, two conditions have been studied. (1) Plug and (2) SOC. Charging is controlled by charge power generation (CPG) controller whose inputs and outputs are as follows:

- The nominal active power.
- The number of cars in charge.
- Threshold K4 of value 0.5 which is the same in the case of GRC. This controller passes the first input to the second input when the input crosses the threshold.

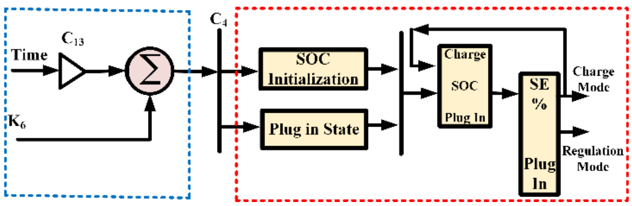

FIGURE 8. Control diagram for EVs in regulation and charging mode.

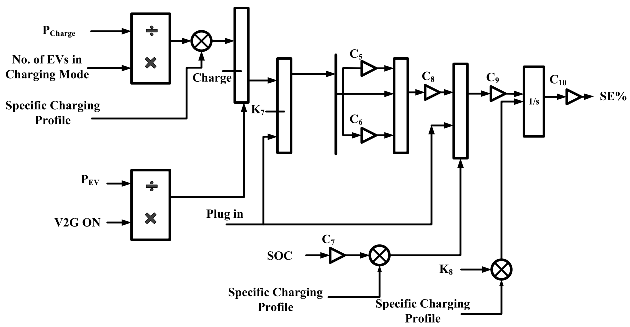

FIGURE 9. The layout of the SOC controller.

Total EVs fleet is divided into five groups. Each group has its own charging profile which is stochastic in nature and dependent upon charging time and converter station availability. Car profiling has been done on the basis of plug in time and State of SOC. Fig. 8 illustrates the methodology to determine whether the car is in the charge state or the regulated state.

To limit output changes resulting from plug state and SOC initialization, two limiters have also been incorporated in designing of SOC controller. The value of these limiters is 1×10^4 for positive values and 11×10^{-4} for negative values which provide a reasonable estimate. Fig. 9 indicates the state of the charge controller. Salient features for this controller are as follows:

- The state of charge controller requires precise information on the active power of EVs in charging mode.
- It also requires the total number of EVs which are in charging mode.
- SOC controller also requires information about the number of cars in regulation mode (discharging mode) and the number of cars in charging mode. Charging profile description (ranging from 1 to 5) of a specific EV fleet is also required.
- It also requires a bounded output of SOC and charging states, which is available to us through limiters.
- State Estimation (SE, described in %) of EVs also checks whether the car is in charging or in regulation mode, so a switch is placed which interchange these two modes alternatively. When charging is complete, the controller terminates the charging process.
- SOC also checks the plugging of vehicles. If the vehicle is unplugged, zero value is placed which ultimately stops or terminates charging.

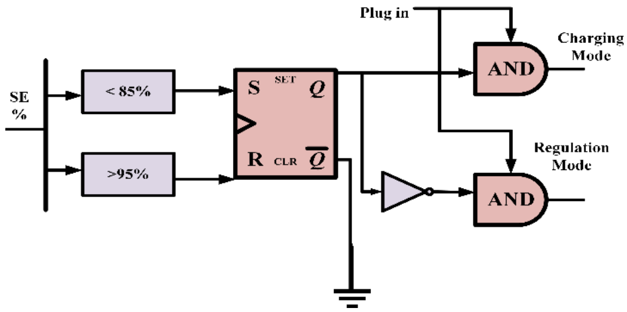

FIGURE 10. Control diagram for EVs charger controller.

Two direct gains (naming C14 and C15), which improve the efficiency of charging and discharging process, are also designed whose values are as follows:

$$C14 = \zeta$$
$$C15 = 1/\zeta$$
$$(\zeta \text{ is the efficiency})$$

By multiplying the state of charge with 3.6×10^6, real-time kilo wattage can be obtained, which is sent to an integrator as initial condition and plug state as its main input. The output of the integrator is multiplied with the capacity and number of cars to obtain state estimation.

After state estimation calculation, EVs are inspected for mode detection (regulation or charging). Fig. 10 indicates the layout of the charger controller.

Features and description of the charger controller are as follows:

- To ensure high-quality power output, SE has been set within 95% to 85%, otherwise, the charging process will be terminated.
- If SE is less than 85%, cars are in charge mode and when it reaches greater than 95%, cars will be in regulation mode.

IV. SYSTEM MODELLING AND SIMULATION

In the proposed model, important parameters in consideration are converter efficiency, capacity, power, and the total number of EVs in the fleet. The proposed model also has an option for enabling and disabling of V2G mode. The charging station also consists of a central rectifier and DC-DC converter with buck-boost configuration. The rectifier converter transforms the AC waveform to the unidirectional DC output. Buck-Boost DC converter then transforms the DC output voltage to desired levels. This charger strategy is bidirectional in nature meaning that it can provide and consume power between grid and charging station.

Nominal Power of PV farm is 8MW and solar farm tripping is simulated at 12 noon which indicates cloudy weather during the day. Wind farm power is 4.5 MW while nominal wind speed is 13.5 m/s. The wind farm will disconnect from the system when wind speed increases to 15 m/s and connect automatically when wind speed reaches its nominal speed.

TABLE 1. Simulation parameters of the proposed model.

Parameters	Value	Parameters	Value
Wind Power (MW)	4.5	K8	8.5 x 10^4
Wind Speed (m/s)	13.5	C1	2
Max Speed (m/s)	15	C2	4000
PV Power (MW)	8	C3, C9, C17	-1
Diesel Generator (MW)	15	C4, C7, C8, C12	1 ∠120
Nominal Frequency (Hz)	50	C5, C10	0.333
Dead Band (p.u)	0.001	C6, C11	0.67
SOC_{min}	0.2	C13, C18	1/60x 60
SOC_{max}	0.8	C14	$1/\zeta$ (1/0.9)
SOC_d	0.6	C15	ζ (0.9)
K1, K2, K3, K4, K5, K7	0.01	C16	3.06^8
K6	1	C19	100

The wind profile model is implemented in MATLAB through a binary search method over a period of 24 hours. Wind farm trips at 10:00 pm (22 hours) when wind speed crosses the maximum threshold level.

The nominal power of the diesel generator system is 15MW and voltage is kept at 25kV with a nominal frequency of 50Hz. The main purpose of the diesel generator is to balance the power demand when there is some disturbance in the microgrid. Diesel generator equals power supply and load demand as it is connected to the power grid, where any change in grid frequency can be observed through its rotor speed.

A. SYSTEM MODEL PARAMETERS

The state of charge of different cars in a fleet is divided into 5 types. Type 1 includes cars where there is a charging station in the parking lot and the owner can charge his car during office hours. Cars in type 2 can be charged in office parking lots, but due to longer rides, charging time is less. Type 3 cars cannot be charged in offices & can only be charged at home. Cars in type 4 fleet can be charged all day. Type 5 cars' fleet can only be charged at night.

Table 1 shows the parameters of the charging station used in the simulation.

V. RESULTS AND DISCUSSION

In this section, different contingencies have been simulated over a course of a day and the proposed charging strategy has been checked for frequency regulation. These contingencies include (i) Reduced power output of PV farm (ii) Tripping of Wind turbine and (iii) Starting of Asynchronous Load (iv) Simultaneous disturbance in solar and wind farm. Each disturbance or contingency in a microgrid is checked for frequency regulation for three different conditions. In the first condition, the V2G mode is disabled. In the second condition, V2G mode is enabled and the third condition includes an increased number of EVs during V2G mode.

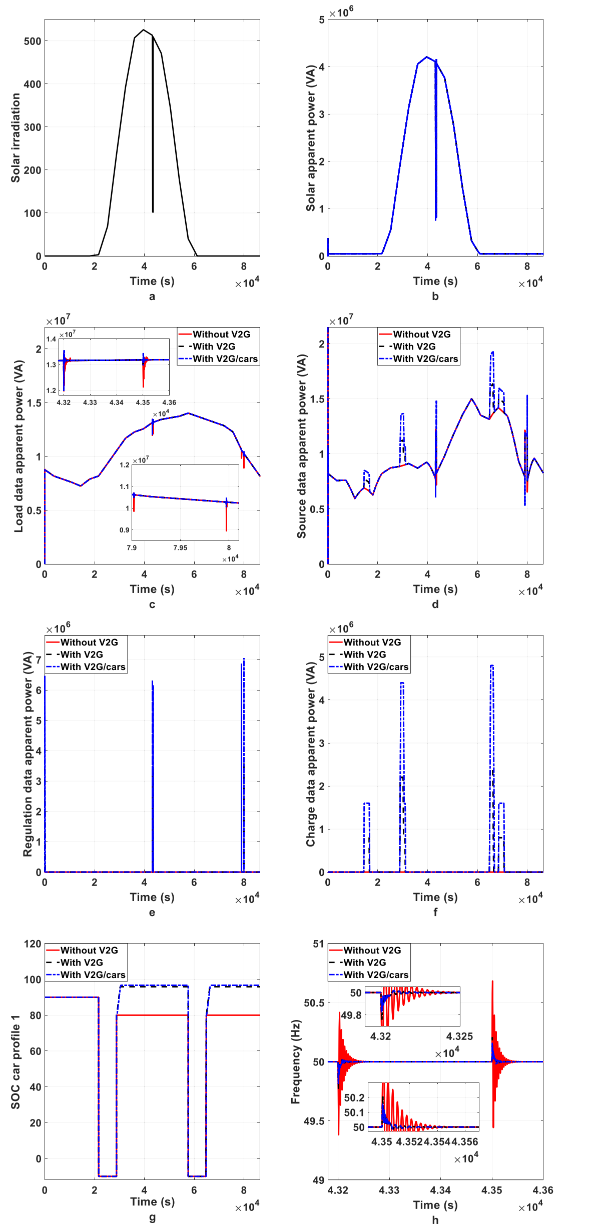

FIGURE 11. Primary frequency control during PV farm disturbance with V2G mode in different scenarios. (a) solar irradiation (b) solar apparent power (c) Total Load (d) total generation (e) Regulation mode (f) Charging mode (g) EVs SOC profile (h) PFC through different scenarios.

A. CASE A: MAJOR REDUCTION IN PV FARM OUTPUT

In the first case, the simulations for major load reduction of PV farms are performed. During a cloudy day, PV farm power reduces dramatically, and it generates power only up-to 20 percent of its rated capacity. The power output graph of such an event is shown in Fig. 11a [26] and 11b. The total load and generation of the industrial microgrid are shown in Fig. 11c-d. In Fig. 11c-d, it can be seen that the solar farm initially produces power at around 25,000 sec (07 am), and then it starts increasing. However, at 43,200 sec which is exactly 12 noon, there is a steep dip in solar power which indicates power reduction to 20% of nominal power. This steep dip remained there for around 05 minutes and exactly after 43500 seconds, the solar power starts generating power to its full capacity. Fig. 11f shows the operation of the V2G when the generation is greater than the load then EVs remain in the charging mode. Similarly, if the load is greater than the generation, then the EVs will be in the regulation mode (discharging mode) as seen in Fig. 11e. The system has five cars profiles and Fig. 11g shows the SOC of car profile 1 for three different scenarios.

Each disturbance in the industrial microgrid is checked for frequency regulation under three different scenarios. For the first scenario, the V2G mode deactivates the primary frequency as seen in Fig. 11h that is illustrated in red color. In the second scenario, when V2G mode is activated as shown in Fig. 11h, rapid stability, and change were observed in the IMG frequency as illustrated in black color. Similarly, in the third case, as the number of EVs in the fleet increases then the industrial microgrid frequency will be improved to an even higher level, as illustrated by the blue color in Fig. 11h.

When V2G mode is disabled during the partial shading, then only charging of EVs can be performed, so that vehicles just act as load without regulation of power grid. As it is seen from the Fig 11h, frequency is stable at 50Hz when solar power produces nominal output power. As soon as power drops to a significant level, there are sudden dips in frequency which corresponds to under-frequency at 43,200 secs. Under-frequency occurs as the PV farm produces significantly lower power output. Minimum frequency deviations during this event are around 49.5Hz which is enough to make microgrid unstable. After 5 minutes, when solar power comes back to its original or nominal power then there is a sudden increase in frequency which depicts the over frequency event. Frequency jumps to around 50.7Hz which again causes grid disturbance that is not acceptable. These sudden spikes can cause grid instability and need to be avoided at all costs. Thus, the PV farm's reduced output power affects microgrid stability.

When V2G mode is turned on as shown in Fig. 11h, immediate stabilization, and improvement are observed in the grid frequency. It is evident from the figures, that by enabling V2G mode, the regulation is provided by EVs in terms of active and reactive power through bidirectional power flow, and hence, an improvement in the grid frequency is observed. When solar farm produces low output power at 43,200 seconds, the frequency drops to 49.8Hz, which is well within limits. Also, fewer flickers are observed during this event, which accounts for improved power quality. Moreover, during the time when power from the PV farm comes back to its nominal output power at 43,500 sec, then the V2G again stabilizes the frequency and prevents microgrid from the over-frequency problem. Variations are only around 0.4%Hz with improved power quality. Thus, it is confirmed from simulations, that V2G does indeed pave the way towards improved microgrid frequency.

Initially, only 100 cars were considered in the V2G fleet. When the number of EVs in the fleet increases, then the grid frequency improves to even better levels as shown in Fig. 11h. Frequency simulation depicts that primary frequency can be controlled to an even better level by increasing the number of EVs. Thus, the V2G mode accurately performs the desired function. A summarized table of the frequency deviation of all mentioned cases is given in Table 2.

TABLE 2. Comparison for different V2G scenarios during solar farm reduced output.

Mode	Min. value of frequency	Max. value of frequency
V2G off	49.42	50.75
V2G on with 100 vehicles	49.79	50.2
V2G on with 200 vehicles [12]	49.8	50.17
V2G on with 200 vehicles	49.81	50.16

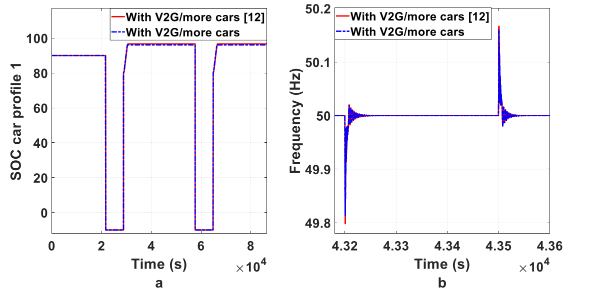

FIGURE 12. The proposed primary frequency control (PFC) and the PFC [12] during PV farm disturbance with V2G mode in different scenarios. (a) Charging mode (b) EVs SOC profile (h) PFC through different scenarios.

In Fig. 12, comparisons between the proposed primary frequency control (PFC) and the PFC technique used in [12] have been performed. In this figure, it can be noticed that the proposed PFC has better results performance in comparison to the PFC in [12] for the frequency and SOC car profiles. Moreover, these results with better performance by the proposed PFC are confirmed and listed in Table 2.

B. CASE B: WIND FARM TRIPPING

In this case, wind farm simulations are carried out. Wind farm trips when wind speed exceeds 15m/s which is its maximum speed limit. This is to protect the wind turbine from getting damaged due to high wind speed. The wind farm connects to the grid again when the wind speed reaches its nominal speed (i.e. 13.5 m/s). The wind profile data for 24 hours is obtained through BSM (Binary Search Method) in MATLAB. Fig. 13 shows a typical wind profile for a time period of 24 hours [26]. It can be seen that wind farms tripped at 79,200 sec which corresponds to 10:00 pm or 22:00 hrs. During this time, wind speed is greater than the upper set point of 15 m/s and after some time, it returns back to normal power when the wind speed comes back to nominal limits. The system has five car profiles and Fig. 13c shows the SOC car profile 2 for three different scenarios.

Fig. 13b depicts the scenario during the tripping of a wind turbine when V2G mode is disabled. It is evident from the figure, that as soon as the wind turbine trips

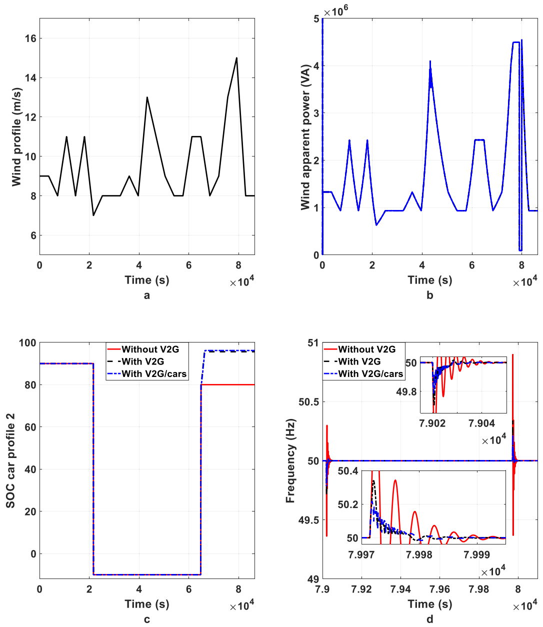

FIGURE 13. Frequency graph during wind farm tripping with V2G mode in different scenarios. (a) Wind profile (b) wind apparent power (c) EVs SOC profile (d) PFC through different scenarios.

TABLE 3. Comparison for different V2G scenarios during wind farm tripping.

Mode	Min. value of frequency	Max. value of frequency
V2G off	49.36	50.9
V2G on with 100 vehicles	49.7	50.35
V2G on with 200 vehicles [12]	49.74	50.29
V2G on with 200 vehicles	49.8	50.21

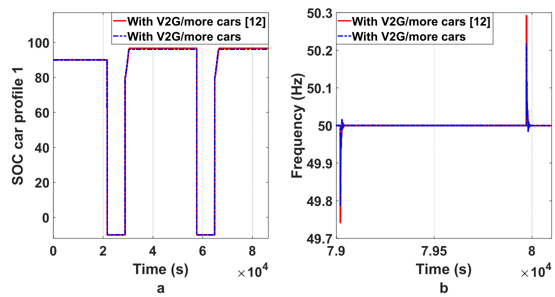

FIGURE 14. The proposed primary frequency control (PFC) and the PFC [12] during PV farm disturbance with V2G mode in different scenarios. (a) Charging mode (b) EVs SOC profile (h) PFC through different scenarios.

at 79,200 seconds, the grid instantaneously responds to it by exhibiting under-frequency behavior with a minimum value of 49.36Hz. It is to be noted that this dip is stronger than the case of a solar farm because, during the night, solar output is also zero. This decline in frequency is enough to make the grid unstable and the load must be shed in order to cope up with this negative impact on the grid. Also, when wind farm restores to its energized state, a frequency spike is observed, which corresponds to the over-frequency case in the grid. The frequency of the system during this event is almost equal to 51Hz, which is again dangerous as this is the upper limit at which industrial microgrid can collapse and cannot recover. Thus, when V2G is off then the EVs cannot contribute to grid regulation, and that further worsen the situation when the wind farm is tripped.

When V2G mode is turned on, then the EVs in the microgrid contribute to frequency regulation and improves the stability of the microgrid when any disturbance occurs in the form of source tripping. Fig. 13d elaborates on the situation when the wind farm is tripped with V2G mode enabled. By looking at Fig. 13d, it is evident that V2G mode contributes significantly to grid frequency, which is obvious from the improved values of the frequency. The lower value of frequency is around 49.7Hz while the upper-frequency limit is around 50.35 Hz.

By increasing the number of EVs in the fleet from 100 to 200, the frequency of the grid is improved to more acceptable limits as presented in Fig. 13d. Moreover, by increasing the number of EVs, frequency further stabilizes in both under and over-frequency domains. This is a significant achievement as in practical scenarios, thousands of EVs are present in the microgrid. Hence, when the number of EVs increases more and more, then the frequency of the microgrid will improve accordingly. Thus, the robustness of V2G mode is achieved by increasing the number of EVs in the fleet. A summarized table of the frequency deviation of all mentioned cases is given in Table 3.

In Fig. 14, comparisons between the proposed primary frequency control (PFC) and the PFC technique used in [12] have been performed. In this figure, it can be noticed that the proposed PFC has better results performance in comparison to the PFC in [12] for the frequency and SOC car profiles. Moreover, these results with better performance by the proposed PFC are confirmed and listed in Table 3.

C. CASE C: STARTING OF ASYNCHRONOUS LOAD

In this case, the impact of load on grid frequency is considered. In previous cases, it was seen that V2G helped in mitigating frequency deviations up to acceptable margins when there is tripping of renewables from the grid. In this scenario, there is an induction machine, which kicks off at noon. It is a well-known fact that as soon as the induction motor starts, it will destabilize the grid frequency and it cannot recover for some time if the nominal power of an asynchronous machine is high. Starting current is in the order of 6 to 8 times, which can cause sudden inrush current in the system. Fig. 15 shows the starting of the induction machine at noon (43,200 secs).

As shown, the asynchronous machine kicks at 12 pm, which coincides with reduced solar output power. This is a real-life scenario because 12 noon is a peak industrial time and during a windy day, solar output is also reduced. This affects the microgrid frequency, as two events occur simultaneously which causes instability of microgrid frequency.

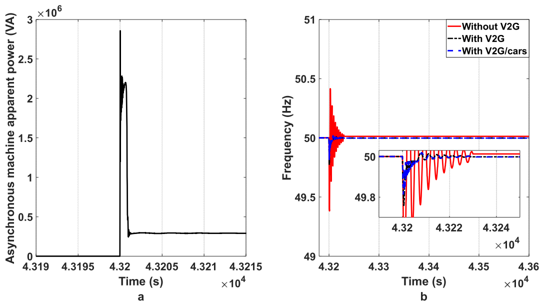

FIGURE 15. The asynchronous machine at noon (a) apparent power (b) PFC.

TABLE 4. Comparison of different V2G scenarios during asynchronous machine starting.

Mode	Min value of frequency
V2G off	49.4
V2G on with 100 vehicles	49.77
V2G on with 200 vehicles	49.83

Industrial microgrid frequency for the scenario when V2G mode is disabled is shown in Fig. 15b. In this case, the frequency declines to 49.4Hz and thus negatively affect the grid. Before the events, frequency is stable at 50 Hz, but as soon as the asynchronous machine starts along with reduced solar power, primary frequency instantly drops to 49.4 Hz and recovers after some flickers. After two seconds, frequency deviations are reduced and after 15 seconds, the frequency is again stabilized but still oscillating around 50 Hz.

When V2G mode is enabled, the EVs start contributing to grid regulation and minimizes frequency deviations to lower values, which indicates the stabilization of grid frequency as shown in Fig. 15b. Evident improvements in frequency deviations can be observed in Fig. 15b. Previously, when V2G mode was disabled, the frequency was 49.4Hz, but when V2G mode is enabled the frequency is improved to 49.77 Hz.

As in the previous scenario, it can be seen that by increasing the number of cars in the EV fleet, frequency deviations can be further reduced, which is a practical case as there are thousands of vehicles in the EV fleet connected to the grid as shown in Fig. 15b. When 100 more cars are added to EV fleet then the frequency variations are further improved from 49.77 Hz to 49.83 Hz. This shows that if more cars added, then the frequency deviations can be further reduced to a more minimum value. A summarized table of the frequency deviation of all the mentioned cases is given in Table 4. This table depicts clearly, that the increasing number of vehicles in the EV fleet can bring positive changes in the grid.

D. CASE D: SIMULTANEOUS POWER REDUCTION OF SOLAR FARM AND TRIPPING OF WIND FARM

In this case, solar farm power is decreased dramatically meanwhile, the wind farm also trips at the same instant. This combined disturbance is enough to cause the grid to destabilize. The power output of these two sources can be seen in Fig. 16. It can be observed from the figure that wind farm is tripped and the solar farms produce very low output power (with a factor of 0.2) around 12:00 pm for a small period of time. Here Y-axis shows the apparent power in MWs for the wind and solar farms. The impact of this simultaneous disturbance on the grid frequency can be noticed.

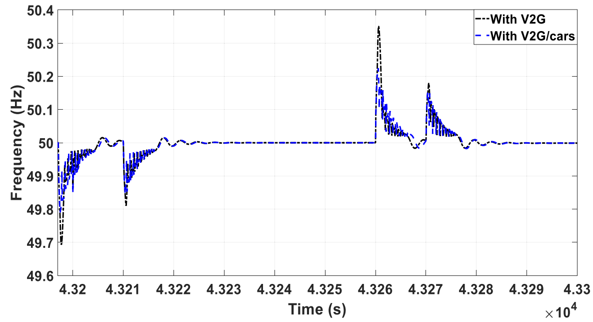

FIGURE 16. Frequency graph during simultaneous solar and wind farm disturbance with V2G mode enabled and with 200 EVs.

TABLE 5. Comparison for different V2G scenarios during simultaneous wind and solar farm disturbances.

Mode	Min. value of frequency	Max. value of frequency
V2G on with 100 vehicles	49.69	50.33
V2G on with 200 vehicles	49.8	50.22

When V2G mode is enabled, then EVs act as a source and provide power stored in their batteries to improve the frequency of industrial microgrid. This injected power can regulate grid frequency through the grid regulation controller as shown in Fig. 16. It is evident from the figure that V2G does contribute to severe grid fluctuations due to the disturbances in the wind and solar farms. Previously, high peaks in frequency were observed but as soon as V2G mode is enabled, the frequency of microgrid gets stable and peaks are at a much lower value as expected.

As seen in the previous scenario, when the number of vehicles is increased, then it further stabilizes the frequency and improves grid stability. This case is no different as shown in Fig. 16. It is evident from the figure that by adding more EVs, more reserve is added in the grid, which in turn provides stability to the grid. The frequency graph depicts that, when solar and wind farm trips, then there is some disturbance in the grid in the form of under-frequency but it is within acceptable limits. Also, when wind and solar farm gets back to their nominal powers, an over-frequency scenario occurs as observed in the previous cases but this frequency is also within the allowable limits and doesn't affect the microgrid. A tabular comparison of this case is given in Table 5.

VI. CONCLUSION

This paper studies the impact of EVs' charging on an industrial microgrid. The control scheme is implemented through grid regulation and charger controllers which provide bidirectional power flow. This dual power flow not only provides charging power to EVs but also ensures frequency regulation through active and reactive power support. The charging station consists of a central AC/DC VSC station that injects power into an industrial microgrid and minimizes frequency deviations. Different contingencies have been simulated and their impact on primary frequency is observed. Simulation results prove that the proposed bidirectional charging strategy contributes effectively towards frequency regulation. The frequency is well regulated within the acceptable margin when V2G mode is enabled for EVs' charging/discharging as compared to when V2G mode was disabled. Frequency regulation improves even further by increasing the number of EVs in the fleet as more vehicles contribute to grid regulation mode. Hence, simulation results prove the robustness of the proposed controllers.

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SHEERAZ IQBAL (Member, IEEE) received the B.E. degree in telecommunication engineering from Allama Iqbal Open University, Islamabad, Pakistan, in 2010, the M.S. degree in electronic engineering from International Islamic University, Islamabad, in 2014, and the Ph.D. degree in electrical engineering from North China Electric Power University (NCEPU), Beijing, China, in 2020. He has served as a Lecturer at the Department of Electrical Engineering, The University of Azad Jammu & Kashmir, Muzaffarabad, Pakistan, from 2014 to 2017. He is currently a Lecturer with the Department of Electrical Engineering, The University of Azad Jammu & Kashmir. His research interests include primary frequency control, MG energy management, and electric vehicles integration in industrial MG.

AI XIN (Member, IEEE) received the B.S. degree from the Nanjing Institute of Technology (now Southeast University), Nanjing, China, in 1985, the M.S. degree from the China Electric Power Research Institute, Beijing, China, in 1988, and the Ph.D. degree from North China Electric Power University (NCEPU), Beijing, in 1999, all in electrical engineering. He was a Senior Research Scholar with Brunel University, London, U.K., in 2003. He was the Director of the Institute of Power Systems, where he was involved in research and teaching on power system and automation. He is currently a Professor and a Doctoral Tutor with the School of Electrical and Electronic Engineering, NCEPU. His current research interests include power system analysis and control, frequency regulation, and energy management of microgrid.

MISHKAT ULLAH JAN received the B.Sc. degree in electrical engineering from the University of Engineering and Technology, Bannu, Pakistan, in 2010, and the M.S. degree in electrical engineering from the CECOS University of IT and Emerging Sciences, Peshawar, Pakistan, in 2014. He is currently pursuing the Ph.D. degree in electrical engineering with North China Electric Power University, Beijing, China.

From 2010 to 2011, he worked as a Trainee Engineer under the National Internship Program at Sarhad Hydel Development Organization, Pakistan. From 2014 to 2015, he worked as a Research Associate with CECOS University, Peshawar. His research interests include power system stability, frequency regulation, and energy management of microgrid.

MOHAMED ABDELKARIM ABDELBAKY received the B.Sc. and M.Sc. degrees in electrical engineering from Cairo University, Egypt, in 2013 and 2016, respectively. He is currently pursuing the Ph.D. degree with the School of Control and Computer Engineering, North China Electric Power University, Beijing, China.

He joined the Department of Electrical Power and Machines Engineering, Cairo University, as an Associate Lecturer, in 2016. His current interests include nonlinear and economic model predictive control, their stability analysis, and their applications in wind energy conversion systems, power plants, and power system frequency regulation.

HASEEB UR REHMAN received the B.S. degree in electrical engineering from the University of Engineering & Technology, Bannu, Pakistan, in 2010, and the M.S. degree in electrical engineering from the University of Engineering & Technology, Peshawar, in 2016. He is currently pursuing the Ph.D. degree in electrical engineering with North China Electric Power University, Beijing, China.

From 2012 to 2017, he worked as an Engineer Distribution with Sui Northern Gas Pipeline Ltd., Pakistan. His research interests include the integration of renewable energy source in microgrid and frequency stability and control of microgrid through virtual synchronous generator.

SALMAN SALMAN received the B.E. degree in electrical engineering from the Baluchistan University of Engineering and Technology, in 2011, and the M.S. degree from CIIT Islamabad, Pakistan, in 2015. He is currently pursuing the Ph.D. degree in power system with NCEPU. His research interests include impacts of PV and battery storage in microgrid environment, generalized modeling of EV, and PV and battery storage for a secure and modern grid.

SYED ASAD ABBAS RIZVI received the B.S. degree in electrical engineering from the Pakistan Institute of Engineering and Applied Sciences, in 2014. He is currently pursuing the Ph.D. degree in electrical engineering and automation with North China Electric Power University. His research interests include electric vehicles, renewable energy, DERs integration in power grid, and market participation.

MUHAMMAD AURANGZEB received the B.S. degree from the Department of Electrical Engineering, COMSATS University, Abbottabad, Pakistan, in 2013, and the M.S. degree in power system and automation from Hohai University, Nanjing, China. He is currently pursuing the Ph.D. degree in electrical engineering with North China Electric Power University, Beijing, China. His research interests include power system stability, power system protection, electric vehicles scheduling, and electricity markets.