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Reduction of Frequency Deviation on Microgrid by Coordination of Electric Vehicles in a Charging Station

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Abstract: *A microgrid is a low inertial power system. As a result, the frequency deviation of the microgrid is greater than that of the national grid, and the integration of charging stations further affects the frequency deviation in the microgrid. Utilising Plug-In Electric Vehicles (PEVs) with battery storage devices for grid support through the Vehicle-to-Grid (V2G) concept can reduce frequency deviations, thereby enhancing microgrid stability. An effective algorithm-based control charging station with Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G), and Vehicle-to-Vehicle (V2V) modes of operation is designed and implemented in this work for efficient Electric Vehicle charging and microgrid support.*

Keywords: *Electric Vehicle (EV), Vehicle to Grid (V2G), Vehicle to Vehicle (V2V), Charging Station (CS), Charging Mode (CM)*

I. INTRODUCTION

Coal, petroleum products, and natural gas are the most commonly used fuels in today's energy environment. Continuous use of these fuels leads to pollution, environmental damage, and other health issues. As a result, shifting to renewable energy and electric mobility is essential. The integration of renewable energy sources is an effective way to meet electricity demand sustainably. The primary issue with renewable energy is its dependence on weather and environmental conditions, which results in fluctuating power generation. This has an impact on the system's power quality, reliability, and stability. Hence, it becomes the most challenging task to integrate renewable energy sources, such as wind and solar, into the grid. The wind system, in particular, creates additional complications in frequency regulation. When generation and demand are not matched, the frequency deviates from its nominal value. When generation exceeds demand, frequency increases. When generation falls short of demand, the frequency falls. An energy storage system is utilised to mitigate such changes and achieve a consistent output.

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Power. There are various types of energy storage systems available, including Battery Energy Storage Systems (BESS) [1], Ultracapacitors, and spinning reserves. The electric vehicles can act like a BESS, and they can be included in the frequency support of the micro-grid by Vehicle to Grid (V2G) technology and can replace BESS, having a high installation cost. According to the National Electric Mobility Mission Plan (NEMMP) 2020, India plans to deploy 5 to 7 million electric vehicles nationwide. Electric Vehicles (EVs) have been identified as the major frequency regulation agents (on the demand side) due to their inherent ability to provide instantaneous frequency support [2]. EVs remain idle for almost 96% of the time, making them suitable agents for providing adequate frequency support. V2G mode offers a range of services, including active power support, reactive power compensation, and support for renewable energy sources. When electric vehicles are idle, V2G delivers adequate energy to the grid. As a result of this process, EVs provide economic benefits to their owners. EVs may store extra energy supplied by renewable energy sources in batteries. When generation exceeds demand, energy is stored in batteries; when generation is insufficient, EVs supply electricity to the grid. As a result, EVs can be used to maintain a stable frequency at a constant level. EVs can be effectively charged at a charging station [3] situated in parking areas, such as those found in industries, offices, etc. Since AC charging (also known as slow charging) is more suitable for Electric Vehicles, EVs are frequently charged in this mode, which requires a significantly longer time. Hence, the EVs that are parked nearby for half a day to charge can help facilitate V2G and V2V coordinated charging. The author of [4] discusses a Mixed Integer Linear Programming (MILP) based method for effective charging and V2G feeding, taking into account the number of EVs connected to charging, as well as their battery level (SoC) and capacity [5]. Discussed the most efficient charging techniques, coordinated charging, and a dual tariff approach for grid frequency support, as well as a dual tariff method for lowering charging costs and increasing income. In [6], the author connected EVs to the grid for grid frequency support, and the EVs' output is sent into the grid whenever the grid's frequency varies. The capacity and SoC of the battery are not considered in the analysis. In [7], a novel energy management solution is proposed for incorporating Plug-In Electric Vehicles (PEVs) with Vehicle-to-Grid (V2G) capabilities into the operation of grid-connected micro-grids, with and without reliable prediction information. The proposed technique, when used with the MAS framework, is effective at managing V2G in microgrids. In [8], the frequency regulation of

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The source has been examined using Battery Energy Storage System (BESS) technology to accurately monitor and control the storage system, thereby extending the battery's life. The work in [9] describes the micro network layout of an electric car charging station, including its components, bi-directional DC/DC and AC/DC converters, and important charging station control modes, such as off-grid discharging and charging. In [10], many types of fast charging technology and regular charging plugs, as well as their respective ratings, have been discussed. Chademo and Combined Charging System (CCS) [11] are two different types of charging ports that are widely utilized around the world. In this work, we propose a control algorithm to keep the micro-grid frequency deviation to a minimum by coordinating the EVs in a charging station. The microgrid frequency and State of Charge (SoC) of the EVs are constantly monitored by the controlling algorithm. The switching of this mode is based on the frequency of the microgrid. The proposed control algorithm supports G2V, V2G, and V2V. When the frequency is high, the load is increased, and when the frequency is low, the load is reduced, allowing power to be fed back to the grid. The system responds quickly because this algorithm is based on fuzzy logic control and has a low computational level and constraints. From the literature review, it is observed that an algorithm that effectively addresses frequency deviation through coordinated charging in all three modes—namely, Grid to Vehicle, Vehicle to Grid, and Vehicle to Vehicle—has not been developed to date. The coordinated recommendation and scheduling of EV charging sites, addressing both the optimization problem of EV-charging station (CS) matching and scheduling as well as the problem of benefit distribution among the participating charging stations, is presented [12]. A multi-input, multi-output model predictive control-based approach to satisfy the load frequency control requirements in EVs has been proposed [13]. A novel distributed algorithm aimed at coordinating a large population of EVs to enhance the resilience of urban energy systems is proposed [14]. Coordination of Opportunistic EV Users at Fast Charging Station with Adaptive Charging is proposed [15]. Multi-Objective Coordinated Planning of Distributed Generation and Electric Vehicle Charging Station is proposed [16]. Deep reinforcement learning has been used for the optimal coordination of electric vehicles [17].

The main contributions of this work are,

(a) Development of a simple and elegant algorithm that helps in the coordinated charging of electric vehicles in all three modes (G2V, V2G, and V2V) in a charging station.

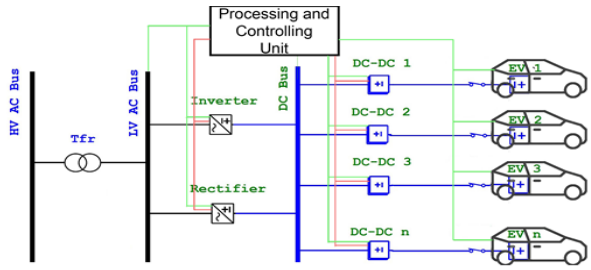
(b) The algorithm effectively regulates the frequency deviation in the microgrid by controlling the SoC of the battery.

The materials and methods used in the work are described in the next section.

II. MATERIALS AND METHODS

A. Charging Station

In the future, a significant penetration of EVs into the grid can lead to an abundance of charging points in parking areas. Making the charging station smart offers more benefits than a standard charging station, as it provides electrical conversion, monitoring, and safety functionality. The charging station with V2G and V2V support helps EV owners to have financial benefits. It gives a better frequency regulation for the grid. The charging station in remote areas, such as industries and buildings, can utilise a secondary power supply unit. The Vehicle-to-Vehicle (V2V) technology implemented in a charging station is useful to EVs during power unavailability from the main supply. In this type of charging, the EV with a higher SoC can charge an EV with a lower SoC. In this, EVs share a common DC link to exchange power between them, so no additional cost is incurred.



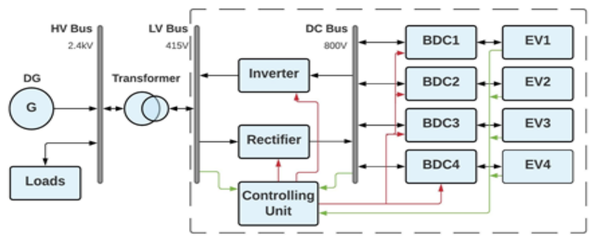
[Fig.1: Basic Structure of the Charging Station]

The charging station under consideration, which consists of the following components, is shown in Fig. 1.

1. DC-DC Bidirectional converter (BDC) [18] for charging electric vehicles with current controllers that charge the vehicle based on battery parameters. The BDC can also transfer power in both directions.
2. The AC-DC Rectifier [19] is used to supply power to electric vehicles. It is a voltage-controlled rectifier that maintains a constant DC voltage as well as any current imbalance.
3. The DC-AC Inverter [20], has a power controller by which the output power can be controlled during grid feeding or Vehicle to Grid (V2G) [21].
4. A controlling unit that gathers information about the SoC and capacity of the EV and the microgrid frequency. The control signals are generated based on the frequency of the system by analyzing the SoC of the EVs to charge or discharge.

B. Problems of Uncoordinated Charging

When the EVs in a charging station are not coordinated in the system as shown in Fig. 2, the EVs connected to the Charging Station are charged at all grid frequency conditions. Since the vehicle charging in this mode starts at a peak time of the grid system, which increases the peak load in the grid, it causes increased power losses, voltage drops, and undervoltage at the most critical buses [22].



[Fig.2: Structure of the System]

C. Coordinated Charging Control Algorithm

The impact of uncontrolled

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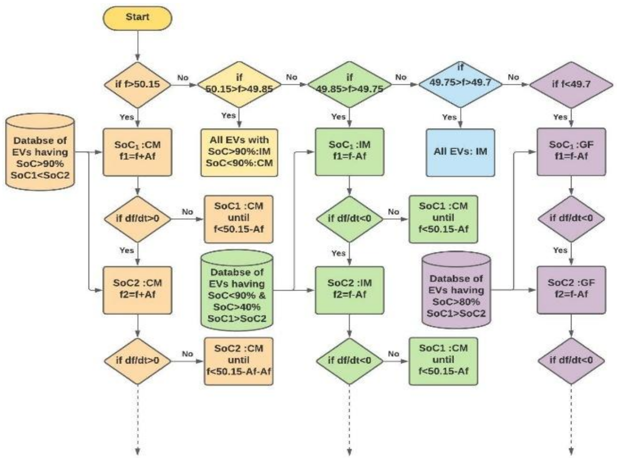
and controlled charging of plug-in hybrid electric vehicles on the distribution grid has been discussed in [16]. From the literature, it is observed that an algorithm that takes care of the number of EVs connected to a charging station has not been developed to date. It is essential to manage the number of EVs in a charging station, as the frequency stability in a microgrid depends on the number of EVs connected to the station.



[Fig.3: Basic Structure of Algorithm]

Hence, a novel algorithm is proposed that effectively takes care of the frequency deviation in the micro grid by controlling the frequency, SoC of the battery, and the number of EVs. It should also be mentioned here that it is the first attempt to reduce the frequency deviation by controlling the power flow to EVs in a microgrid. The algorithm is simple, elegant, and based on fuzzy logic. The various steps involved in developing the proposed algorithm are described in the subsequent sections.

For achieving micro-grid frequency support, an effective control mechanism is required. The controlling unit consists of a processing unit that operates according to a set of instructions, known as an algorithm. By controlling the power flow in and out of the charging station in coordination with EVs, the grid frequency deviation can be significantly reduced. A basic structure of the algorithm that has been developed is shown in Fig. 3.

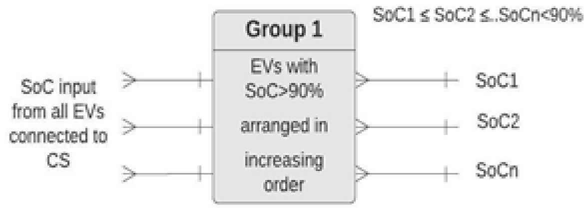
The different inputs to the algorithm are frequency, SoC of EV battery, and the number of EVs connected to the charging station. In this method, a group of EVs are classified based on their SoC value as follows. EVs with SoC greater than 90 % are classified in group 1, EVs with SoC 40 % to 90% in group 2, and EVs with SoC greater than 80% in group 3. These EVs in each group perform different actions at different frequencies.

- *Frequency: 50.15 ≥ f ≥ 49.85Hz:*

When the frequency lies in this region, 50.15 Hz is taken as the rated frequency. EVs in group 1 are made to be in idle mode. I.e., the EVs with a SoC greater than 90% are in an idle state, which is not charged until all EVs are fully charged to 90%. When all EVs connected to the charging station reach 90%, the set level is changed, and the EVs are charged to 100%.

- *Frequency: f > 50.15Hz:*

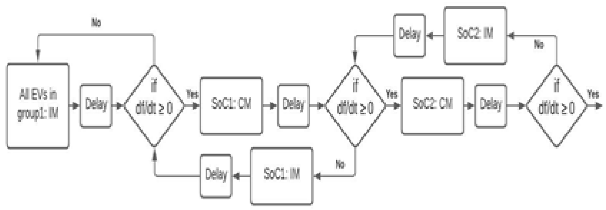
When the frequency is above the rated frequency (f = 50.15 Hz), the microgrid's power generation exceeds the demand side. By increasing demand, the power imbalance can be reduced, allowing the frequency to be lowered. Because of this, reserved EVs with SoC greater than 90% are used for the grid frequency support.



[Fig.4: Grouping and Sorting of EVs in Group 1]

When the frequency rises above 50.15 Hz, the EV with the lowest SoC in the group, as shown in Fig. 4, enters charging mode (CM), increasing the load on the demand side. This causes the rate of change of frequency (df/dt) to decrease.

After a delay, when this df/ dt >0, the frequency is again rising, and at this condition the EVs with SoC2 are made to be in charging mode (CM), causing a further decrease in the df/dt, this process continues till 'df/ dt' <0 or charging of EVs in group 1 completes. The framework of group 1 EVs is shown in Fig. 5.

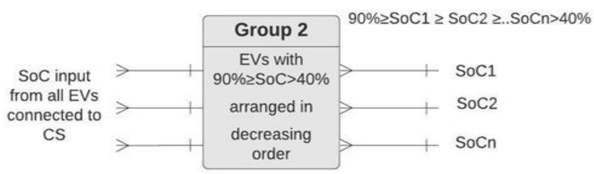


[Fig.5: Framework of Group1 EVs]

When the frequency falls below 50.15 -Δf_1, the charging of group 1 is terminated. The Δf_1 is the frequency change when the EV with SoC1 is connected to the grid. Thus, the frequency deviation above the frequency (f = 50.15 Hz) is controlled by the group1 EVs.

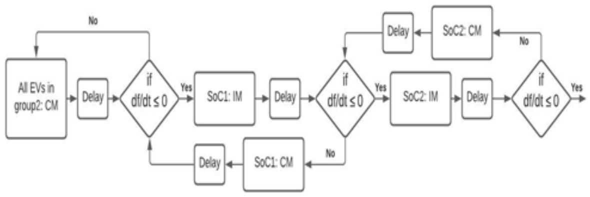
- *Frequency: 49.85Hz > f > 49.75Hz*

When the frequency falls below 49.85 Hz, the generation is less than the demand, and to maintain stability, either generation needs to be increased or consumption needs to be reduced. In this algorithm, consumption is reduced by having the EVs connected to the charging station in an idle state. The group 2 EVs achieve this. The grouping and sorting of EVs in the group are illustrated in Fig. 6. The EV with the highest SoC in group 2, SoC1, is disconnected or placed in Idle Mode (IM), resulting in a reduction in grid consumption.



[Fig.6: Grouping and Sorting of EVs in Group 2]

After a delay, if the df/dt <0, then the SoC2 will be in IM, and this process continues till the 'df/ dt'> zero or till the EVs in group 2 are all in IM. Thus, the frequency regulation is achieved by keeping the EVs with SoC <40% in IM.



[Fig.7: Framework of Group 2 EVs]

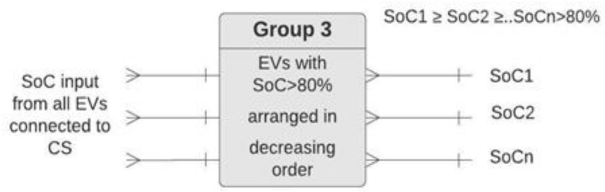
This process is ended when the frequency rises above 49.85 Hz or falls below 49.75 Hz. When the frequency increases above 49.85 Hz, all EVs in Group 2 will be in CM; when the frequency drops below 49.75 Hz, all EVs in Group 2 will be in IM. The framework of group 2 EVs is shown in Fig. 7.

- *Frequency: 49.75Hz >f ≥ 49.70Hz*

All EVs in the CS are in idle mode when the frequency is between 49.75 Hz and 49.7 Hz. Thus, all charging of EVs has been suspended until the frequency is above 49.75 Hz. When the frequency rises above 49.75 Hz, the EVs return to charging mode.

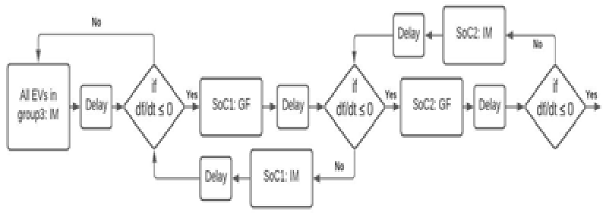
- *Frequency: 49.70Hz <f <45Hz*

When the frequency falls below 49.7 Hz, all the EVs are in idle mode. To further reduce the frequency drop at this stage, V2G mode is applied, i.e., grid feeding.



[Fig.8: Grouping and Sorting of EVs in Group 3]

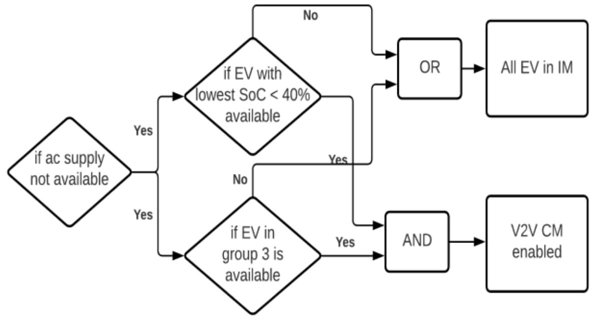
The EVs in Group 3, with a SoC greater than 80%, participate to support the grid frequency. The EV with the highest SoC (SoC1) is selected for grid feeding (GF). After some delay, if df/ dt is negative, the SoC2 also supports GF. The grouping and sorting of EVs in the group are shown in Fig. 8.



[Fig.9: Framework of Group 3 EVs]

Since the grid feeding is achieved by transferring power from the EVs to the grid, also known as the V2G method, the EV owner also benefits in terms of revenue or a discount on the EV charging price. The price of V2G is higher than that of G2V, and thus, there will be savings at the end of the charging period. The framework of group EVs is shown in Fig. 9.

When the input power to the CS is unavailable, the EV can be charged via V2V. The charging of the EVs with the lowest SoC is done by the EVs having the highest SoC. The charging also depends on the availability of EVs. The power transfer is done via the DC bus in the CS. Hence, in the V2V mode, the EV owner of a higher SoC gets benefits from the CS. The algorithm for the above V2V mode is shown in Fig. 10. This algorithm checks whether there is any availability of EVs with the lowest SoC (<40%) and EVs in group 3. If both EVs are available, the power is transferred from the EV with the highest SoC (>80%) to the EV with the lowest SoC via DC bus or DC link.



[Fig.10: V2V Algorithm]

III. RESULTS AND DISCUSSIONS

A varying frequency source is required to investigate the Charging Station's operation. The input power is supplied by a Distributed Generation source, which generates constant power and has a voltage governor to control the output voltage. The loads are used to alter the microgrid's power consumption. By varying the loads at different times, the frequency is varied to create various test conditions. The charging station comprises a rectifier, an inverter, and a bidirectional DC converter. The rectifier is the component that converts AC power to DC power. This DC power is then transferred to the EV's battery using a bi-directional charger, as shown in Fig. 2. The standard parameters of the charging station are listed in Table I.

Table 1: Parameters of Charging Station

	Parameter	Value
LV Bus	V(rms)	415 V
	Frequency (f)	50 Hz
DC Bus	Vdc	800 V

In this case study, 4 EVs are considered with parameters as shown in Table II.

Table 2: Parameters of Electric Vehicle

	SoC	Parameter
EV1	95%	Nominal Voltage = 320 V
EV2	62%	
EV3	35%	Rated Capacity = 100Ah
EV4	92%	

The charging station with a controlling unit consists of an inverter, rectifier, and bi-directional converter. By incorporating the proposed algorithm, the frequency deviation in the microgrid can be reduced. The frequency of both unregulated (blue) and regulated (red) EVs is compared, along with the mode of operation, as shown in Fig. 11. When power generation is reduced due to uncoordinated charging, the EVs continue to charge at a lower frequency, causing the frequency to deviate even further. When the generation is kept constant, the demand-side power consumption remains unchanged, and the system's frequency rises; therefore, the frequency deviation is greater in a low-inertial microgrid. It

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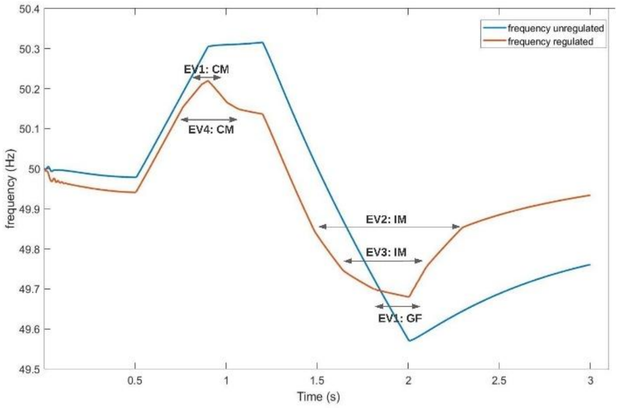
can be seen that in the unregulated frequency curve, f_{max} =50.32 Hz and fmin = 49.57 Hz and the peak-to-peak frequency deviation is 0.75 Hz. In the regulated frequency curve, fmax = 50.22Hz and fmin = 49.68Hz. Peak to peak difference is 0.54Hz.



[Fig.11: Mode of Operation of EV at Different Frequencies]

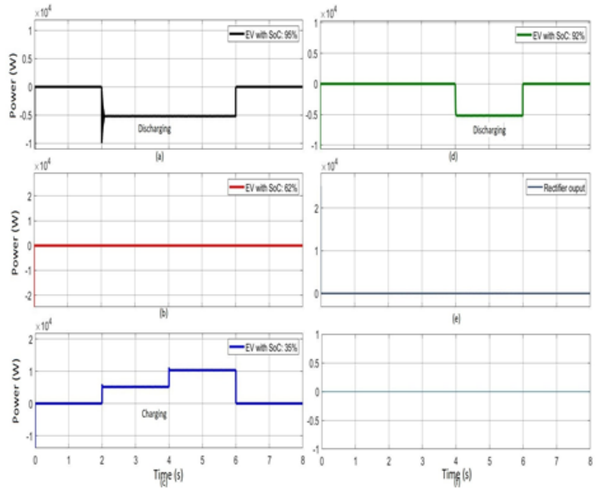
Hence, it can be concluded that when the charging station operates in coordination with EVs, the frequency deviation in the microgrid is reduced.

Table 3: Different Modes of EVs for Grid Support

	Mode of Operation	Start - End Time (s)
EV1(SoC: 95%)	CM GF IM	0.846 – 0.934 1.818 – 2.035 otherwise
EV2(SoC: 62%)	IM CM	1.482s – 2.293 otherwise
EV3(SoC: 32%)	CM IM	otherwise 1.639 – 2.095
EV4(SoC: 92%)	CM IM	0.760 – 1.106 otherwise

The operation mode of EVs under different frequencies is shown in Table III. This switching of EVs to other modes is performed by the control signal generated by the algorithm, as follows. When the frequency rises above 50.15 Hz, the EV4 starts to charge, which is the EV with the lowest SoC in the group. As a result, df/dt is reduced. Again, if the observed frequency is above 50.15 Hz, EV1 also switches into charging mode, which is the EV with the highest SoC in the group. During this time, the df/dt is reduced further. Later, when the frequency falls, EV1 is switched back to idle mode, followed by EV4. Now the frequency falls within the rated frequency range. After a time, the frequency falls again to cross 49.85 Hz, causing the EV2 to change its mode from charging mode to idle mode. As a result, df/dt increases, and the frequency falls to 49.75 Hz, causing the EV3 to transition from charging mode to idle mode. The frequency again falls to 49.7 Hz, and at this time, EV1 starts to grid feed, or operates in V2G mode. The df/dt becomes much less since the grid frequency begins to increase. Hence, EV3 and EV2 return to charging mode gradually.

The power flow during the coordination of EVs for grid support is shown in Fig. 12(a-f). The power flow of EV1 (EV with SoC = 92 %) is shown in Fig. 12(a). It can be observed that the EV is in charging mode from 0.846 s to 0.934 s, as during this time, the grid frequency is greater than 50.15 Hz.



[Fig.12. (a) Power Flow of EV1(SOC 95%) (b) Power Flow of EV2 (SOC 62%) (c) Power Flow of EV3 (SOC 35%) (d) Power Flow of EV4 (SOC 92%) (e) Rectifier Output (f) Inverter Output]

From 1.818 s to 2.302 s, the EV is in grid feed mode since the frequency is less than 49.7 Hz. For all other times, the EV1 remains in idle mode. The power flow of EV2 (EV with SoC =62%) is shown in Fig. 12(b). It can be observed that EV2 remains in idle mode from 1.482 s to 2.293 s to reduce the frequency deviation. For all other times, it is in charging mode. The power flow of EV3(EV with SoC = 35%) is shown in Fig. 12 (c). The EV remains in idle mode from 1.639 seconds to 2.095 seconds. For all other times, the EV is in charging mode. The power flow of EV 4(EV with SoC = 92%) is shown in Fig. 12(d). It can be observed that the EV is in grid feed mode from 0.760 s to 1.106 s to stabilise the frequency. For all other times, the EV is in idle mode. The power output of the rectifier is illustrated in Fig. 12(e). It can be observed that the power output remains constant at 20 kW up to 0.760 s. At this time, EV4 starts charging, and the power output increases to 30 kW in 0.846 seconds. At this point, EV1 shifts to charging mode, and the power output increases to 40 kW. At 0.934 seconds, EV1 shifts from charging mode to idle mode, and hence the power output decreases to 30 kW. At 1.106 seconds, EV4 enters idle mode, and hence the power output decreases to 20 kW. At 1.482 seconds, EV2 enters idle mode, and consequently, the power output decreases to 10 kW again. From 1.639s to 2.293s, none of the EVs are in charging mode, and hence the power output of the rectifier is zero. It is also worth noting that the inverter power output is high from 1.818 s to 2.035 s, as EV1 enters grid feed mode during this time, as shown in Fig. 12(f). From the results, the frequency change before and after coordinating EVs in a charging station with the same load is given in Table IV. From the data in Table IV, it is observed that the maximum frequency decreases by 0.1 Hz and the minimum frequency increases by 0.11 Hz, resulting in a reduction of 0.21 Hz in the peak-to-peak frequency.

Thus, the frequency is regulated by the coordination of EV by G2V and V2G modes. The charging station is also capable of feeding power back to the grid in V2G mode. To test the efficiency of the algorithm in V2V mode, a complete grid supply failure is given to the system, and the system's

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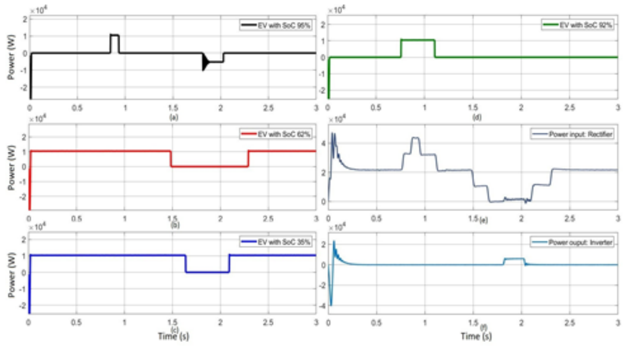
performance is assessed.

Table 4: Comparison of Frequency Change Before and After Coordination of EVs in a CS

CS Mode	f_{max} (Hz)	f_{min} (Hz)	f_{pp} (Hz)
Without the coordination of EVs	50.32	49.57	0.75
With the coordination of EVs	50.22	49.68	0.54



[Fig.13: (a) Power Flow of EV1 (SOC 95%) (b) Power Flow of EV2 (SOC 62%) (c) Power Flow of EV3 (SOC 32%) (d) Power Flow of EV4 (SOC 92%) (e) Rectifier Power Output (f) Inverter Power Output]

When the input power supply to the charging station fails, the EV with the lowest SoC (<40%) has to be charged. For this, V2V mode is used to charge the EV with the help of other EVs. The power flow from EV1 to EV3 during Vehicle-to-Vehicle (V2V) mode is shown in Fig. 13(a-f). The discharging of EVs with SoC 95% is shown in Fig. 13(a). It can be observed that the EV is discharging and delivering power from 2 seconds to 6 seconds. It can be seen that the EV with a SoC of 62% is in idle mode during this time, as shown in Fig. 13(b). During this time, the power flow is 5kW as demonstrated in Fig. 13(c). Between 4 seconds and 6 seconds, EV 4 also participates in V2V charging, and therefore, the charging power is 10 kW. At 6 seconds, both EV1 and EV4 stop delivering power; hence, the charging of EV3 is also stopped. The discharging of EV4 to provide power to EV2 during 4 s- 6 s is shown in Fig. 13(d). The output of the rectifier and inverter, respectively, during V2V charging, is shown in Figs. 13(e) and 13(f). It can be seen that both the powers are zero since there is no power exchange between V2V and G2V during V2V charging.

IV. CONCLUSIONS

The majority of the power generated in the islanded microgrid comes from non-inertial renewable sources and is similarly influenced by the environment. Hence, the frequency deviation in a micro-grid is higher than in the primary grid. This problem of frequency deviation can be addressed with a smart charging station. In this work, an effective algorithm has been developed to make charging stations smart, allowing electric vehicles within a charging station to be coordinated to support grid frequency stability. Only having two constraints reduces the size and complexity of the algorithm, resulting in a faster response. The testing of the proposed algorithm for V2G, V2V, and G2V has been conducted, and the results have been analysed. From the analysis, it is observed that the grid frequency deviation from maximum to minimum before and after coordination has been reduced by 0.21 Hz. This decrease in frequency deviation contributes to grid stability. Since the power is fed to the grid in V2V mode, EV owners will receive revenue and payback based on the extent to which their EV contributes to supporting the grid. As a result, the owner will only have to pay a fraction of the actual price.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/Competing Interests:** Based on my understanding, this article does not have any conflicts of interest.
- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it was conducted without any external influence.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

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