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

**Vidya M. S., Vishnu Chandran**

***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, the integration of charging stations further affects the frequency deviation in the microgrid. Using Plug-In Electric Vehicles (PEVs) battery storage devices for grid support via the Vehicle to Grid(V2G) concept can reduce frequency deviation, resulting in 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 effective 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 causes pollution, environmental damage, and other health problems. As a result, shifting to renewable energy and electric mobility is essential. Integration of renewable energy sources is an effective technique to meet electricity demand sustainably. The main issue with renewable energy is that it is dependent on weather and environmental conditions, resulting in fluctuating power generation. This has an impact on the system's power quality, reliability, and stability. Hence it becomes the most challenging task of integration of renewable energy sources like wind and solar into the grid. Wind system especially creates more complications in frequency regulation. When generation and demand are not matched, frequency is deviated from the nominal value. When generation exceeds demand, frequency increases. When generation falls short of demand, the frequency falls. An energy storage system is utilized to reduce such changes and achieve consistent output power. There are different types of energy storage systems available: Battery Energy Storage Systems (BESS) [1], Ultracapacitors, spinning reserves, etc. The electric vehicles can act like a BESS, and they can include in frequency support of the micro-grid by Vehicle to Grid (V2G) technology and can replace BESS, having high installation cost. In India, according to the National Electric Mobility Mission Plan (NEMMP) 2020, 5 to 7 million electric vehicles will be deployed in the country. 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, which makes them suitable agents for effective frequency support. V2G mode offers a variety of services, including active power support, reactive power compensation, and assistance with 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 provided 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 employed to keep the frequency stable at a constant level. EVs can be effectively charged in a charging station [3] that is situated at the parking areas in industry, offices, etc. Since AC charging (slow charging) is better for Electric Vehicles, EVs are frequently charged in this mode, which requires a sufficiently long time. Hence, the EVs that are parked nearby for half a day for charging can help in 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 for incorporating Plug-In Electric Vehicles (PEVs) with V2G into the operation of grid-connected micro-grids with and without reliable prediction information is proposed. The proposed technique, when used with the MAS framework, is effective at managing V2G in microgrids. In [8], the frequency regulation of the source has been examined using Battery Energy Storage System (BESS) technology to

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correctly monitor and control the storage system and extend 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 normal 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, or power is 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 takes care of the frequency deviation by coordinated charging in all three modes, namely Grid to Vehicle, Vehicle to Grid, and Vehicle to vehicle, has not been developed so far. 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.

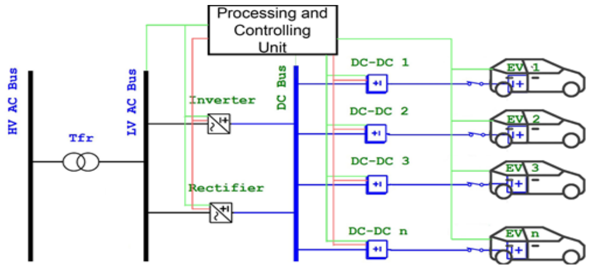
(b) The algorithm takes care of the SoC of the battery effectively to regulate the frequency deviation in micro grid.

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 large penetration of EVs into the grid can cause an abundance of charging points in the parking areas. Making the charging station smart has more benefits than a normal charging station since it provides electrical conversion, monitoring, and safety functionality. The charging station with V2G and V2V support helps EV owners to have financial benefits. It provides a better frequency regulation for the grid. The charging station in remote areas like industries, and buildings can use 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 having a higher SoC can charge an EV with a lower SoC. In this EVs share a common DC link to share the power between them, so no additional cost is needed.



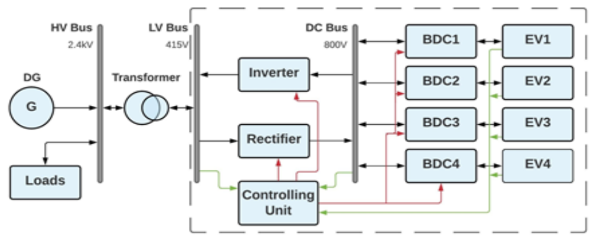

**[Fig.1: Basic Structure of the Charging Station]**

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 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 and controlled charging of plug-in hybrid electric vehicles on the distribution

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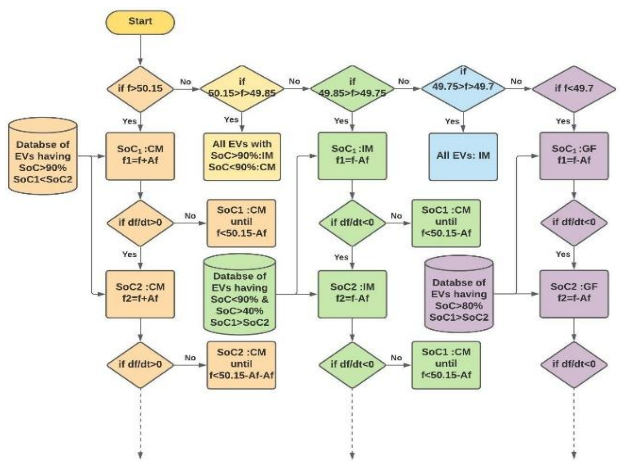
grid has been discussed in [16]. From the literature, it is observed that an algorithm that takes care of the number of EVs connected to a charging station has not been developed to date. It is essential to take care of the number of EVs in a changing station as the frequency stability in a microgrid depends on the number of EVs connected to the charging station [23].




**[Fig.3: Basic Structure of Algorithm]**

Hence a novel algorithm is proposed that effectively takes care of the frequency deviation in micro grid by controlling the frequency, SoC of the battery, and the number of EVs [24]. 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 [25]. The algorithm is simple, elegant, and based on fuzzy logic [26]. The different steps of the development of the proposed algorithm are described in subsequent sections [27].

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

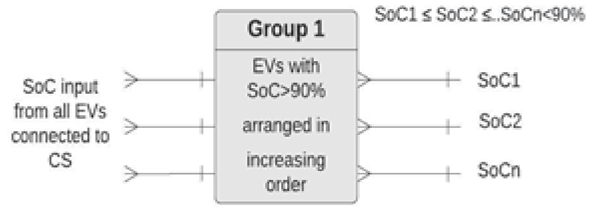
The different inputs to the algorithm are frequency, SoC of EV battery, and number of EVs connected to the charging station. In this method, a group of EVs are classified based on their SoC value as follows. EVs with SoC greater than 90 % are classified in group 1, EVs with SoC 40 % to 90% in group 2, and EVs with SoC greater than 80% in group 3. These EVs in each group perform different actions under 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. Ie., the EVs with SoC greater than 90% are in an idle state which is not charged until complete EVs are charged to 90%. When all EVs connected to the charging station reach 90% then the set level is changed and EVs are charged to 100%.

- *Frequency: f >50.15Hz:*

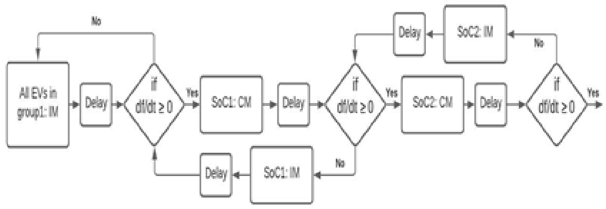
When the frequency is above the rated frequency (f=50.15 Hz), the microgrid power generation is greater than the demand side. By increasing the demand, the power imbalance can be reduced so that the frequency can be reduced. Because of this, reserved EVs with SoC greater than 90% are used for the grid 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 shown in Fig. 4 gets into CM (charging mode) and thus there is an increase in the load on the demand side. This causes the rate of change of frequency (df/ dt) to reduce.

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.

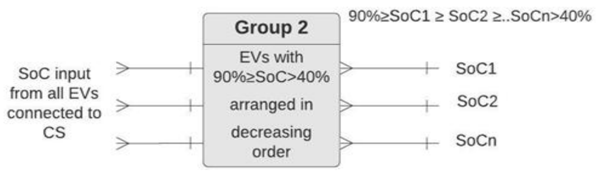



**[Fig.5: Framework of Group1 EVs]**

When the frequency falls below 50.15 -$\Delta f_1$, the charging of group 1 is terminated. The $\Delta f_1$ 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.

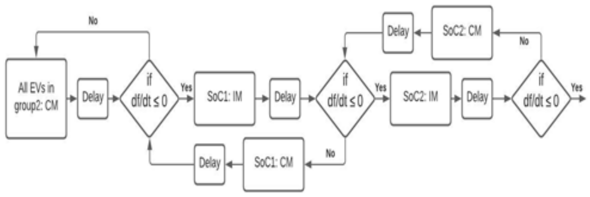
- *Frequency: 49.85Hz >f >49.75Hz*

When the frequency falls below 49.85 Hz, the generation is less compared to the demand and to keep the frequency stable, either generation needs to be increased or consumption needs to be reduced. In this algorithm, the consumption is reduced by making the EVs connected to the charging station to be in an idle state. This is achieved by the group2 EVs. The grouping and sorting of EVs in the group are shown in Fig. 6. The EV with the highest SoC in group 2, SoC1, is disconnected or made in Idle Mode (IM) which causes a reduction in the consumption in the grid.




**[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'>0 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]**

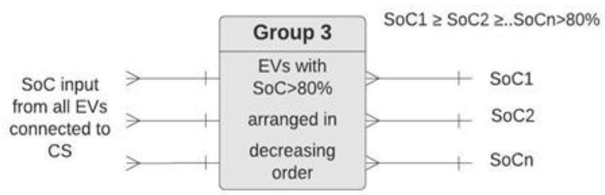
This process is ended when the frequency rises above 49.85 Hz or falls below 49.75 Hz. When the frequency rises above 49.85 Hz all EVs in the group2 will be in CM or when the frequency falls below 49.75 Hz all EVs in Group 2 will be in IM. The framework of group 2 EVs is shown in Fig. 7.

- *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 the charging of EVs is been suspended till the frequency is above 49.75 Hz. When the frequency rises above the 49.75 Hz the EVs are back to charging mode.

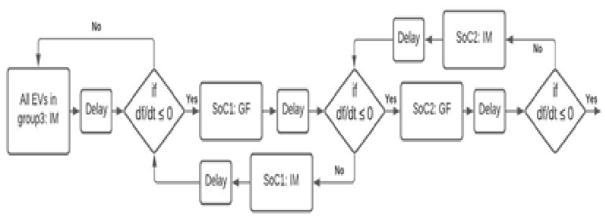
- *Frequency: 49.70Hz <f <45Hz*

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




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

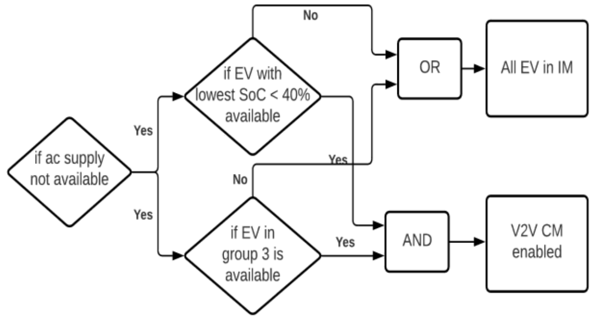
The EVs in group 3 SoC >80% participate to support the grid frequency. The EV with the highest SoC (SoC1) is selected for grid feeding (GF). After some delay, if df/ dt is negative, the SoC2 also supports GF. The grouping and sorting of EVs in the group are shown in Fig. 8.




**[Fig.9: Framework of Group 3 EVs]**

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

When the input power to the CS is not available, the charging of the EV can be done by V2V. The charging of the EVs with the lowest SoC is done by the EVs having the highest SoC. The charging also depends upon 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 different test conditions. The charging station consists of a rectifier, inverter, and bidirectional DC converter. The rectifier is the part that converts the AC power to DC power, this DC power is transferred to the EV's battery by using a bi-directional charger, which is shown in Fig. 2. The common parameters of the charging station are shown in Table I.

**Table 1: Parameters of Charging Station**

| | Parameter | Value |
|---|---|---|
| LV Bus | V(rms)<br>Frequency (f) | 415 V<br>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) is compared along with the mode of operation of EVs is 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 more. When the generation is more keeping the demand side power consumption unchanged the frequency of the system rises, so the frequency deviation is more in a low inertial micro-grid. It can be seen that in the unregulated frequency curve, $f_{max}$ =50.32 Hz and $f_{min}$= 49.57 Hz and the peak-to-peak frequency deviation is

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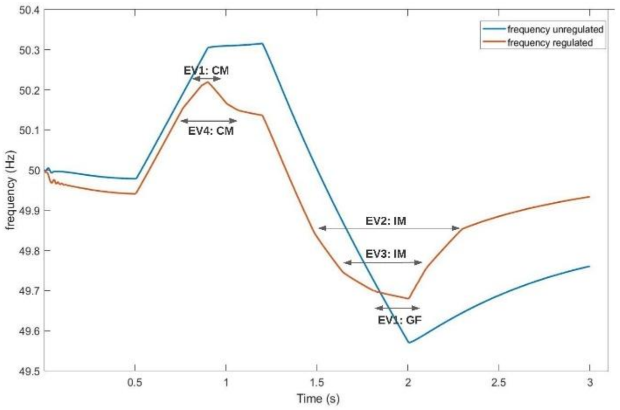
0.75 Hz. In the regulated frequency curve, fmax = 50.22Hz and $f_{min}$ = 49.68Hz. Peak to peak difference is 0.54Hz.




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

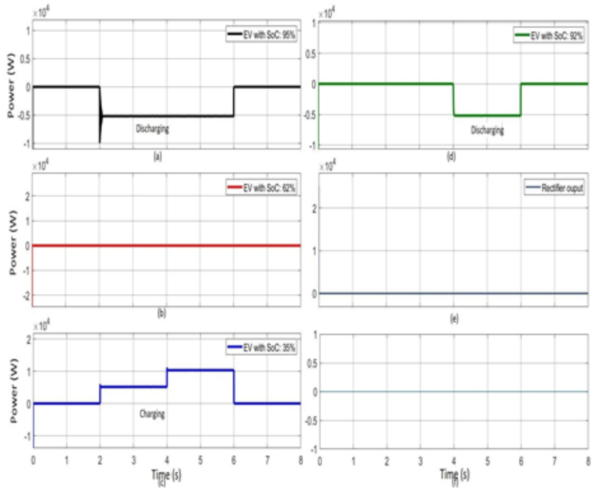
Hence it can be concluded that when the charging station works by coordination of EVs, the frequency deviation in the micro-grid is reduced.

**Table 3: Different Modes of EVs for Grid Support**

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

The operation mode of EVs under different frequencies is shown in Table III. This switching of these EVs to different modes is done 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 frequency observed is above 50.15 Hz, EV1 also is switched 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 lies in the rated frequency region. After a time, delay when the frequency falls again to cross 49.85 Hz causing the EV2 to change its mode from charging mode to idle mode, df/dt increases, and the frequency again falls to 49.75 Hz causing EV3 to change its mode from charging mode to idle mode. The frequency again falls to 49.7 Hz and at this time EV1 starts to grid feed or in V2G mode. The df/dt becomes much less since the grid frequency starts 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 the time 0.846s to 0.934s since during this time, the grid frequency is greater than 50.15 Hz.



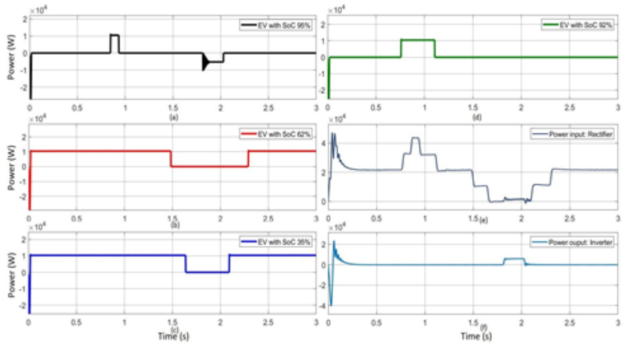

**[Fig.12. (a) Power Flow of EV1(SOC 95%) (b) Power Flow of EV2 (SOC 62%) (c) Power Flow of EV3 (SOC 35%) (d) Power Flow of EV4 (SOC 92%) (e) Rectifier Output (f) Inverter Output]**

From 1.818s to 2.302s, 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 1.482s to 2.293s 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 1.639s to 2.095s. 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 0.760s-1.106s to stabilize the frequency. For all other times, the EV is in idle mode. The power output of the rectifier is shown in Fig. 12 (e). It can be observed that the power output remains constant at 20kW up to 0.760s. At this time, EV4 starts charging and the power output increases to 30kW to 0.846s. At this time, EV1 shifts to charging mode and the power output increases to 40kW. At 0.934s EV1 shifts from charging mode to idle mode and hence the power output decreases to 30kW. At 1.106s EV4 enters into idle mode and hence the power output decreases to 20kW. At 1.482s, EV2 goes to idle mode and hence the power output again decreases to 10kW. 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 may also be noted that the inverter power output is high from 1.818s to 2.035s since EV1 enters grid feed mode during this time as shown in Fig. 12(f). From the results, frequency change before the coordination of EVs and after the coordination of 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 falls by 0.1 Hz and the minimum frequency rises by 0.11 Hz so the peak-to-peak frequency is reduced by 0.21Hz.

Thus, the frequency is regulated by the coordination of EV by G2V and V2G mode. The charging station is also able to feed 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 performance of the system 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 for the charging of this EV with the help of other EVs. The power flow of 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 2s- 6s. It can be seen that the EV with SoC 62% is in idle mode during this time is shown in Fig. 13(b). During this time, the power flow is 5kW as shown in Fig. 13(c). From 4 s to 6 s, EV 4 also participates in V2V charging and hence the charging power is 10 kW. At 6 s, both EV1 and EV4 stop delivering power and hence the charging of EV3 is stopped. The discharging of EV4 to deliver 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 Fig.13 (e) and Fig.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 main 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, which allows the electric vehicles in a charging station to be coordinated to support the grid frequency. 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 done and the results were analyzed. From the analysis it is observed that the grid frequency deviation from maximum to minimum before and after the coordination has been reduced by 0.21Hz. 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 how much their EV supports 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 has no 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 has been conducted without any external sway.
- **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.
- **Authors Contributions:** The authorship of this article is contributed equally to all participating individuals.

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