Integrated Operation of Distributed Resources to Enhance Frequency Regulation in an Isolated Microgrid Environment

K.S.V Phani Kumar, S. Venkateshwarlu

Abstract*:** ***There is a growing concern to be self-sufficient and reduce the dependency on external power generating sources to satisfy the energy demands. Issues such as integrated operation of these power sources without having a dedicated storage system with enhanced frequency regulation is to be addressed. In this paper, the distributed generating sources like solar photovoltaic, diesel generator, fuel cells and electric vehicles are considered. Electric vehicle participation in the frequency regulation comes with constraints on state of charge of the battery and availability of the vehicle. An adaptive-additive algorithm is proposed for performing energy resource management and to maintain the frequency within the allowable band during transient and steady state system conditions. Load variation and EV-fleet availability variations are considered in the paper for understanding the system's response to frequency changes by performing small-signal-analysis. The results show coordinated and satisfactory response of the system to maintain frequency regulation. Economic viability is also focused in the paper.

Keywords **:** ***Distributed generation control, microgrid energy management, electric vehicle, battery management, limited power point tracking, neural network, fuzzy logic***

I. INTRODUCTION

Transportation is taking a new phase all together and the future is based on Battery driven Electric Vehicles (BEV). Electric Vehicles (EV) offer lower costs for running the vehicle per kilometre to the consumer as compared to the traditional IC engine. Very little maintenance, fewer parts for EVs are the features being looked at by the consumers. Battery replacement is a periodic expenditure (running cost) involved but considering the lifetime of a battery to be approximately eight years makes it a feasible choice[1]. Automobile manufacturers such as Nissan and Ford now-a days are making use of eco-friendly/recycled materials for manufacturing EVs.

The sources used for charging these batteries are traditionally internal combustion engines driven by petrol, diesel, gas or grid (with thermal power generators). These sources would lead to air pollution which is to be avoided. The nation's dependency on foreign countries for oil reserves can be reduced by using BEVs. [2],[3] has studied the feasibility of charging the BEVs with solar panels. In this paper, it is assumed that the vehicles get charged from an off-grid SPV (OSPV) installation typically a domestic / non-commercial setup. For domestic rooftop solar, the maximum average capacity installation is 1KWp, and for non-commercial it is 100KWp. Not all the OSPV output is utilized by the loads connected. The BEVs get charged from these stations and utilize the power to commute. The maximum commuting distance before the next recharge can be estimated by the user of the EV. If the battery power available is more than the required power, then the user can decide on connecting the vehicle to the grid.

A standalone microgrid needs precise control of the frequency since most of the loads connected are of induction motor type. [4] suggests and provides the standards for providing ancillary services like frequency regulation and spinning reserve management. Section 3.2 of [5] discusses the frequency tolerance of the grid when the load or power production changes suddenly. The frequency deviation levels were also discussed in detail. Critical loads need high power quality supply which includes Frequency Regulation (FR). The various methods to achieve FR can be broadly classified into two types, one is by controlling the power generation and the other by controlling the load. Synchronous generators present in the system offer inertia to change their present state of generation while other sources like solar, fuel cell and batteries don't have inertia. Micrgrids with renewable sources must be controlled during a disturbance since their power output can vary wildly. These sources must be coordinated and controlled from a central station [6] . Traditionally PI controllers are used [7] for microgrid to perform automatic generation control. [8] focuses on inverter-based control in a microgrid, while the DC source considered is not focused on. Droop control can be introduced to restrict the change in power output when a disturbance happens in the system. This droop control can be modelled as a transfer function [9] and the power output can be controlled. Earlier work [10] has focussed on building the system with PI, Fuzzy and Neural network based controllers to coordinate between the renewable generators. The presence of EVs in the system brings dynamism in the load dispatching and reserve management. In recent times there is an increased focus on Vehicle-to-Grid systems [11], [12], [13] for supporting frequency regulation in the microgrids.

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* Correspondence Author
K.S.V Phani Kumar*, Assistant Professor in CVR College of Engineering, Hyderabad, Telangana, India
Dr.S.Venkateshwarlu, Professor & Head of EEE at CVR College of Engineering, Hyderabad, Telangana, India.

There are numerous papers dealing with the power electronics involved in the load sharing, while many algorithms have been used to make the scheduling of power division [14], but very few have EVs involved for frequency regulation as a spinning reserve[15]. The following advantages can be identified with the involvement of EVs (a) stabilization of frequency (b) quick response (c) economics (d) overall control of fleet. This makes it possible for the algorithm to have primary frequency control in the system. The algorithm shall deal with the constraints regarding maximum and minimum generation capacities of the renewable generators on a timescale and the ramp rates of the generators.

The paper is organized as follows. Section II deals with modelling of the microgrid components such as the load, generators and the controller. The frequency deviation and the role of controllers is discussed in Section III. The Methodology employed in the paper is mentioned in Section IV. Results obtained, and the analysis is discussed in Section V. Finally, the economic feasibility is elaborated in Section VI followed by Conclusive statements and References.

urnal, rectification is not possible.

II. MODELLING OF SYSTEM COMPONENTS

The system considered in the paper is a microgrid with distributed resources connected to an AC system. The sources of power generation considered are Solar Photo Voltaic (PV), Diesel Generator (DG), Fuel Cells (FC) and Electric Vehicle Batteries (BEV). Load on the system consists of both critical and non-critical type. To maintain the power quality, frequency regulation is considered as an important factor in the system. The predicted step load change is assumed to be known by a Central Controller (CC) so that unit commitment and dispatch of power can be done. Each generating component communicates with CC to receive the dispatching signals and sends the status of generation back. The difference between actual load and total power generated is calculated by CC and the change in frequency (dF) is obtained. This dF signal is sent to Local Controllers located at the generating stations to modify the dispatch signal. If frequency gets deviated beyond ±0.05 Hz, then load control is done by CC. The modelling of these components is discussed in this section and the structure is presented in Figure 1.

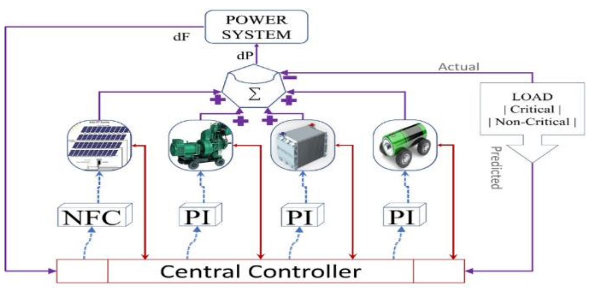

Fig. 1.Block diagram of the microgrid system considered and the information flow

A.Load Modelling

To understand the frequency regulation of the system, the active power demand variation is to be initialized and the change in frequency is to be studied while the generation of power is trying to catch up with the load.

The load and the power generation in this paper are considered in Per-Units (pu). The nominal frequency of the system considered for Indian scenario is 50Hz. The allowable window of frequency deviation according to the grid code has been reduced from 49.70Hz to 49.95Hz and 50.3Hz to 50.05Hz. The traditional way to consider the load variation is in the form of steps. The system's response to this step load change is to be studied in terms of the frequency deviation. The load in a power system shall not be constant but continually varying. In this paper, a combination of step load changes along with White Gaussian Noise (WGN) is considered to have variations in load pattern. This noise signal is governed by two variables, Noise power and Seed. The noise signal is based on the generation of a pure random number with a given mean variation and height of power spectral density called the noise power. The seed corresponds to the repeatability of the sequence of random number generation determined by the sample time used.

A sample of the noise signal generated is shown in Figure 2(a). This signal has rapid variations and does not occur in practical. Hence this signal is passed through a filtering circuit to introduce smoothness. Second order transfer function is considered for filtering the signal. The modified load signal is shown in Figure 2(b). When this signal is added to the constant value say 0.5 pu, the resultant signal looks like Figure 2(c), which appears like a typical load graph. The control system considered for building the load signal is shown in Figure 3.

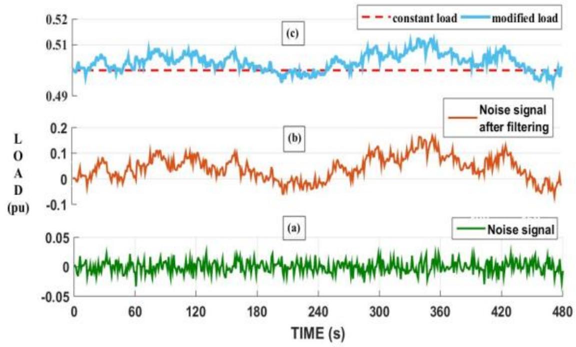

Fig. 2.Flow Generation of Actual Load signal from a noise signal

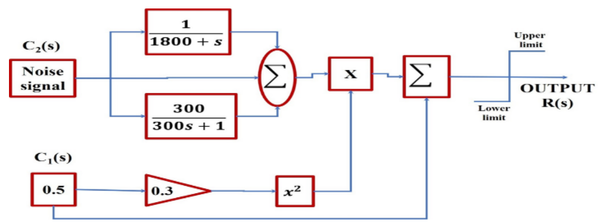

Fig. 3.Generation of Actual load signal using Noise and filters

B.Modelling of Electric Vehicles

Good Each BEV considered in this paper contains a battery that is ready to send its power to the grid, based on the grid requirement. The discharging of the battery depends on the load power requirement. The parameters of the battery that are considered here are initial State of Charge (SoC), in percentage, capacity of the battery (C) in Ampere-Hours, Time Constant (Tc), minimum discharge rate (Dr), Time of plug-in, Time of Plug-out, Number of Series and Parallel combinations of these batteries in each BEV.

As the energy is transferred from battery to the grid, the SoC starts decreasing depending on Dr. The following equation is used for calculating the present value of BEV SoC.

$$SoC_k(t) = 100\left(1 - \frac{1}{C_k}\int_{t_{k_{in}}}^{t_{k_{out}}} i_k(t)\,dt\right) \quad (1)$$

Where $t_{k_{in}}$ and $t_{k_{out}}$ correspond to plugin and plug out times and C(k) is the capacity kth BEV. Where k∈ [1…n]. In this paper, n is considered as five.Based on the estimation of travelling distance before the next recharge, the user of BEV shall decide on the minimum SoC threshold 〖SoC〗_(k,min) so that the discharging of the battery does not happen beyond that limit. The status of BEV connection is decided by CC based on

$$S(k) = \begin{cases} 1 \ if\ SoC_k > SoC_{k,min} \\ 0\ if\ SoC_k \leq SoC_{k,min} \end{cases} \quad (2)$$

CC sends information regarding power needed from BEV fleet. The discharging rate shall not be same for each BEV but depends on the capacity of the battery. Care is taken not to demand more power from a battery since higher discharge rates can affect the health of battery. The overall power supplied from BEVs at the time 't' is the aggregated sum of powers, of connected BEVs, being delivered to the grid.

III. IDENTIFICATION OF FREQUENCY CHANGE AND DISTRIBUTION TO LOCAL CONTROLLERS

The power system considered in the paper is an isolated microgrid with frequency of 50Hz. As mentioned in Section 2, load is expected to change and hence the generation must change proportionately. The system is studied for small changes and hence small signal analysis can be carried out based on [16] a first order transfer function model defined in Equation (3)

$$G_{ps} = \frac{df}{dP_g - dP_d} = \frac{f_{nom}}{f_{nom}D + 2Hs} = \frac{K_{sys}}{1 + s * T_{sys}} \quad (3)$$

Where df is change in frequency, dP_g is change in power generation, dP_d stands for change in load demand, f_nom is the nominal frequency (50Hz), D = dp_d/df. H represents inertia constant. $K_{sys} = 1/D$, taken as 8 and $T_{sys} = 2H/Df_{nom}$, taken as 16.67 sec.The aggregated sum of powers from the distributed generators is compared with the actual load signal to obtain the difference of power production and consumption. This signal is fed to the transfer function given in Equation (3). The output obtained is change in frequency of the system. Depending on the frequency error being positive or negative, the power generation must be increased or decreased, and an equivalent signal must be sent to the generators. This is an additional input to the power generation unit besides the dispatch command obtained from the central controller. There are several modes of operation for the selection of generators [17] like traditional droop control method, adaptive method and the synchronous method. In this paper, the adaptive-additive control method is employed as mentioned in Figure 11 in [10].

A. Designing of Local Controllers

The Local Controllers (LC) play the role of converting the aggregated frequency error signal to the proportional output power change. The Solar PV Generator uses an Artificial Neural Fuzzy Logic Controller (NFC), while the FC, DG and BEV based generators employ Proportional-Integral (PI) controllers.

B. Modelling of PI for BEVs

Each BEV is equipped with a local controller to receive information regarding the change in frequency of the grid. There are two modes of operation considered for frequency regulation in the paper. In the first mode only BEVs handle the entire frequency regulation. If the demand is more, more power is supplied from BEVs, while if demand decreases, power extracted from batteries is reduced. Traditional methods store excess power from the grid in the vehicle and hence need back to back converters for allowing the battery to charge. In this paper, Grid to Vehicle (V2G) is not considered since the batteries would be considered as storage elements in that case.

IV. METHODOLOGY

The system is considered having both critical and noncritical loads. These critical loads require quality in power supply in terms of reliability, low THD and stability in current and voltages. In this paper, the critical loads are aggregated to 0.2 pu. To meet these critical loads like operation theatres, lifts, security systems etc., they are considered as base loads.

Because of the inertia, DG cannot change its output quickly and hence it can be utilized for serving the base loads. If the diesel resource is available, the output of the generator is available, except during scheduled maintenance. In this paper we consider the system operation for 480s sampled at every 0.02 seconds. We assume that diesel and fuel cells have enough resources and are available for power generation at any time.

A. Methodology for Unit Commitment Based on Priority Order

The solar power generation happens day time and the power generated must be connected to the load at its limited power point tracking position [10]. This was achieved by a Neuro Fuzzy controller used to change the output power. When solar power is not available, the load is distributed among BEVs, FC and DG as a priority order. The BEVs supply power to the grid based on the availability of vehicles at the parking stations. The EVs connected to the grid shall be ready to transfer the power to grid based on the command from CC and LC. Hence when the vehicle is available, it is wise to extract power from it as a priority. To deal with the dynamic behaviour of the BEVs, FCs come for rescue by adjusting its output power based on requirement. The CC considers an average discharge rate of the BEVs connected to the parking lot and decides on the power dispatching ability of the parking station. This command is received by the LC at parking station. The distribution of this command among the BEVs can be based on two methods. One is to divide the magnitude by number of BEVs connected and sending it to the BEVs. In this case, the discharge rate of the BEVs will be different since the capacity of the batteries of BEVs are not same.

The other method is to divide the signal to BEVs based on their battery capacities. In this paper the first case is considered for simplicity and in future research the second method shall be implemented under this scenario. Each BEV has a maximum and minimum level of discharge rate based on its battery capacity. If the SoC of the battery is within the permissible limits, the BEV gets connected to the grid and starts transferring power from a minimum to maximum level. If the minimum SoC limit is met, the BEV shall be disconnected from the grid and opportunity will be given to other vehicles waiting to be connected.

B. Control of Solar PV Generation

Solar PV generation is based on the concept of Limited Power Point Tracking (LPPT) achieved by means of NFC [10]. The neural network is trained to remember the Maximum power points and the LPPs for a temperature range of [283 333] K and for an insolation range of [0 1300] W/m2 for about 10,000 samples. 10% of power available from the solar is kept under reserve so that the reliability of the system is enhanced. This is achieved by finding the voltage at which the LPP is available and tuning the output voltage reference value. The system need not depend on the storage devices like battery banks to come as a reserve. This would be a cost-effective method[6] and stationary bulky storage devices and its maintenance can be avoided. In this paper BEVs have batteries, but they are not considered to be storage systems since grid-to-vehicle power transfer is not considered. The SPV power output depends on the insolation and temperature of the panel. For simplicity, the temperature is considered constant i.e., at 300K, while the insolation level is 500W/m2.

V. PERFORMANCE ANALYSIS

The system is simulated using MATLAB R2015b where the mathematical equations pertaining to the generators SPV, FC, DG and BEVs are modelled as described in Section 2, load is modelled with small step changes along with white noise as described in Section 2 of [10]. In this paper two scenarios are considered for analysing the system's performance. The frequency of three system is under study while the system parameters are changing. The nominal frequency considered is 50Hz. While the regulation allowed according to the grid norms is 0.05Hz, i.e., 1% deviation. If the frequency goes beyond 0.05Hz then the quality of the power is considered poor and the critical loads may get affected. In this paper active power load is considered.

The system simulation starts with Zero initial conditions. Hence due to large mismatch between the load and generation there is a high shoot of df (difference of actual and nominal frequency). The system takes an average time of 20 sec to settle. A sampling rate of 0.02 sec, based on the nominal frequency, is considered so that system is analysed every cycle. The simulation is executed for 480 sec. The first step load change is introduced at 100th second and then continued after every 60 seconds. the frequency regulation, the responses of the generators and the adaptability of the control algorithm is under study.

A. Scenario – 1

The following assumptions are made while building the simulation

The SPV, DG and FC are available for generation.

Constant insolation is provided on the solar panels (800 W/m2).

All BEVs are connected to the system.

The priority order for unit commitment considered is minimum generation of DG and FC to handle critical loads, then SPV and BEV. If SPV is utilized (at its Limited Power Point), then BEVs are utilized to the maximum.

The central controller considers the predicted load modelled for the day. Any deviation (introduced by white noise) from the prediction must be dealt with by the local controllers present at the BEV parking station. DG is generating only the minimum power required for satisfying critical loads. Since the necessity for utilizing the reserve is not present, solar is generating power at the limited power point. The variations in the load are typically taken by the BEVs. The FC is available as a standby just in case BEVs doesn't have enough power available to meet load demand. To test the microgrid's ability to meet various ranges of demand, four different cases are taken into consideration here. The average magnitude of the loads is increased from one case to the other and the microgrid's response, mainly the frequency deviation is considered. When a step change occurs in the load demand, the behaviour of the generators is considered and based on the response to the command given.

While the BEVs are sending power to the grid, their capacity decreases and hence SOC of battery is monitored (based on Equation (2)). Based on the input from user 〖(SoC〗_(k,min)), each BEV is automatically plugged off from the grid if SOC of kth BEV falls below the threshold.

1) Case-1

The noise power considered in this case is 10-6 while the seed value used is 23341. The actual load signal generated with and without inclusion of the noise signal is shown in Figure 4. The simulation is run for Time-range of T = 480s. The responses of the system are analysed below.

CC makes the unit commitment decision based on load change predicted. This is shown in Figure 4. Due to the delay in responses of generators, there will be deviation in power balance equation leading to deviation in frequency of the system. The deviation of frequency is shown in Figure 5.

The actual power generated by various sources is shown in Figure 6. From this figure, it is evident that the sources are responding based on CC commands. Local controllers are playing a vital role in ensuring that the power frequency is in tolerable limits.

As mentioned in the algorithm, firstly DG generates the minimum generation of power i.e., 0.1 pu, then the available SPV is allotted which is 0.265 pu. Now FC is committed to its minimum power generation which is 0.1 pu.

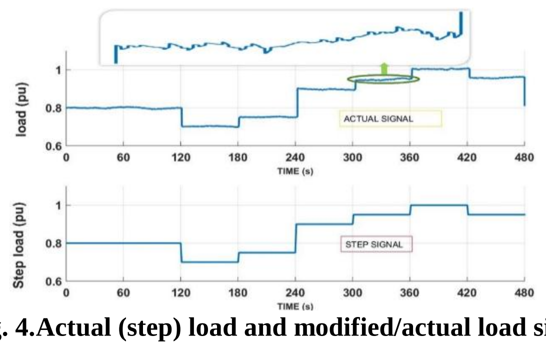

Fig. 4. Actual (step) load and modified/actual load signal

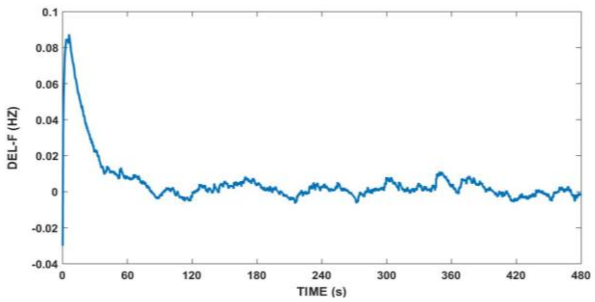

Fig. 5.Frequency change in the system

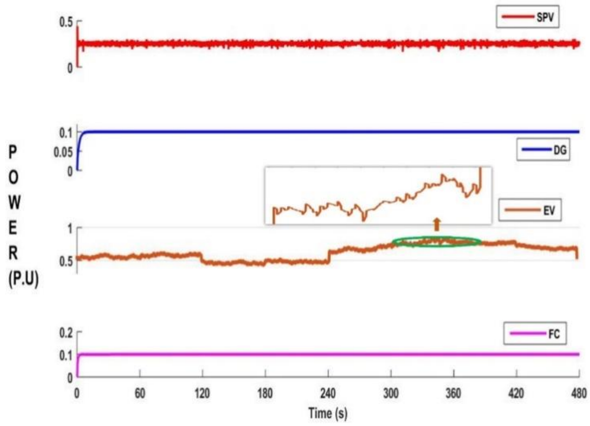

Fig. 6. Active power generation by different sources in the system

The remaining power to be generated is given to the BEVs. In this case, the BEVs can take the variations in the load. There are five BEVs considered in the paper to share the BEV dispatch command. The share of the scheduled power generation is divided among the vehicles based on their capacity of generation. Larger the capacity, more is the share. The power generated by each BEV is shown in the Figure 6. BEVs 4,5 are SUVs while 1,2,3 are hatch models considered. As the batteries of EVs are discharging power, their SoC shall be decreasing depending on the discharge rate. The SoC response of the BEVs is shown in Figure 7. At 360th second, the load has changed from 0.954 to 1.02 pu. Hence there is a requirement for increase in power generation. BEVs have responded to the need and have increased their power generation immediately. As a sample, the SoC of EV-2 is focused in the inset. The rate of decrease of SoC of EV-2 has increased significantly since the rate of discharge demand has increased. When the load demand decreases, the vice-versa happens.

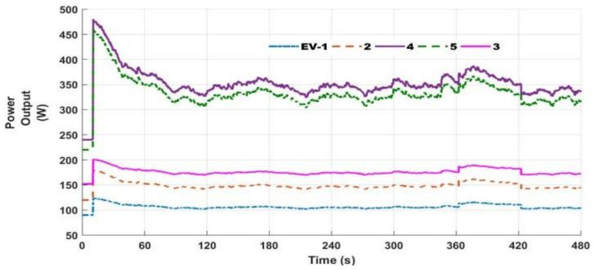

Fig. 7.Power sharing by different BEVs

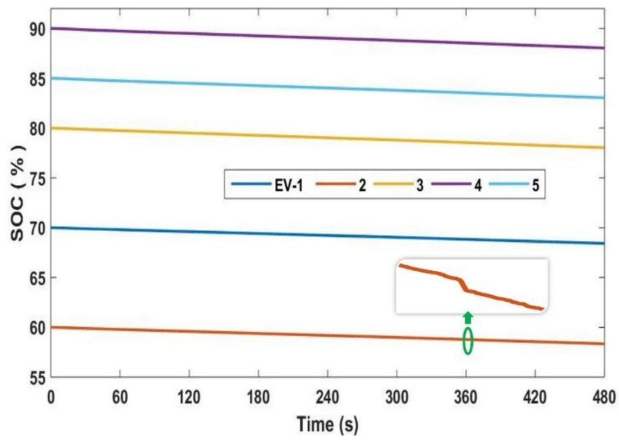

Fig. 8.SoC variation of batteries of EVs with respect to load changes

From the results obtained in this case it is evident that the system is capable of handling frequency excursions and maintain the frequency error within the allowable limits.

2) Case-2

The load levels have been increased to test the system's capability to withstand the dynamics. The noise power considered in this case is 10-5 while the seed value used is 500. The noise levels have also been increased to analyse the transient behaviour of the system. The actual load variation is shown in Figure 9. At 120th and 240th second there is a major step load change (of about 0.2 pu) in the system. The frequency deviation is shown in Figure 10. The BEV fleet is adjusting its output without much effect on the frequency deviation. The BEV power output is shown in Figure 11.

The load sharing by Solar PV, FC, DG and BEVs is shown in Figure 12. There isn't much change in the outputs other than BEV's, since the EVs are assumed to be able to deliver the power to the load.The inset shows variation of EV. Since the noise power levels were increased in the load signal, there is considerable transient in BEV's output. Since the ramp rates of the battery care considerably faster, the frequency has not deviated much.

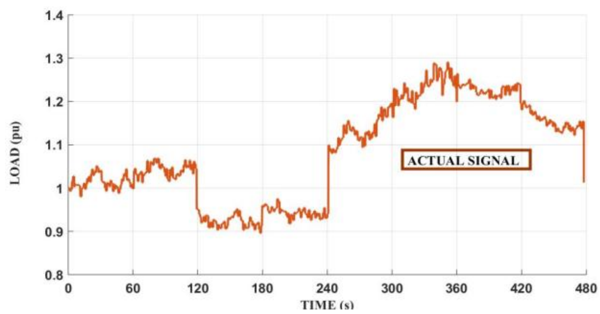

Fig. 9.Actual load signal considered in the system
Fig. 10.

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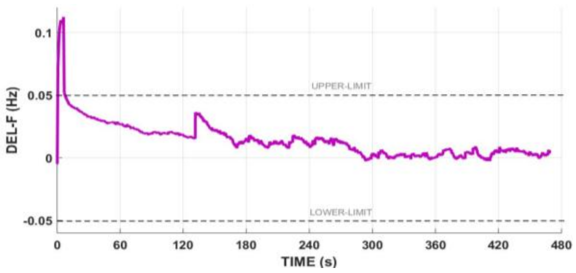

Fig. 11. Frequency change in the system due to load change

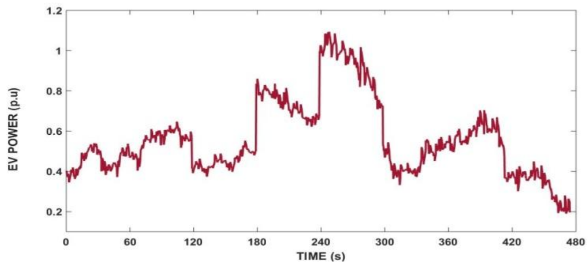

Fig. 12. Power delivered to grid by BEV fleet

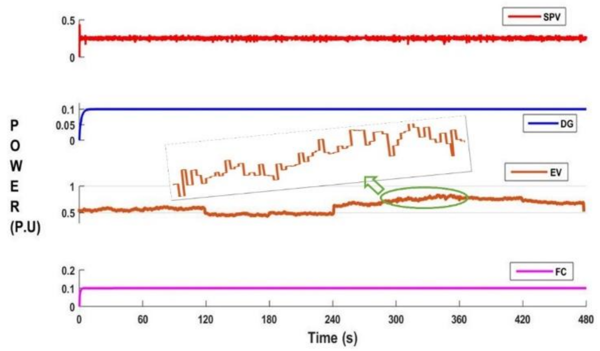

Fig. 13. Active power generation by different sources in the system

3)Case-3

The noise power considered in this case is 5*10-3 while the seed value used is 250. The Figure 13 shows load variation considered in this case. A maximum load demand of 1.56 pu is considered. The BEVs are ready to discharge their power to the grid at a much faster rate safely within the prescribed SOC limits. The frequency deviation obtained in this case is shown in Figure 14. The frequency deviation is restricted between 0 to 0.02 Hz.

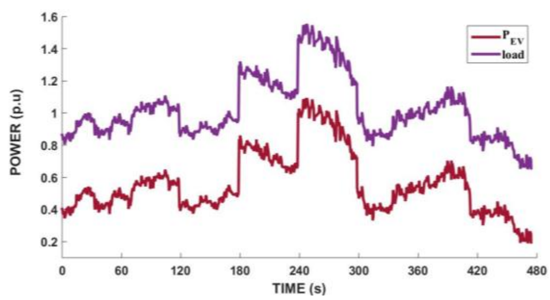

Fig. 14. Actual load signal along with the power delivered by the EV fleet

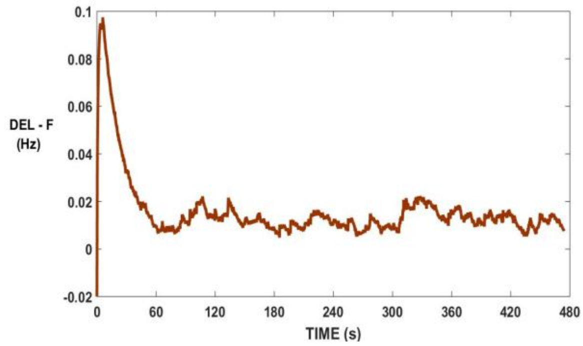

Fig. 15. Frequency change in the system due to load change

The three cases have considered a wide spread variation of load signals with step and random variations. These results show that BEVs can handle the frequency regulation of the system in coordination with the other generation sources in the system. The frequency deviation is well within the prescribed limits of ±0.05 Hz. The SOCs of batteries and power generation by BEVs is not projected here.

B. Scenario – 2

If the SOCs of BEVs have fallen below the allowable limits or the user of the vehicle has opted for a plug-in or plug-out, the sum of power availability of the BEV fleet shall vary, and the system must adapt to the changes. In this scenario, three such cases shall be taken into consideration as shown in Table-1 and the behaviour of the system shall be analysed. The availability of a BEV 'k' shall now be considered so that total power from BEV fleet is known for CC.

One more modification is considered in this scenario regarding the maximum generation capabilities of each generator. The maximum possible load that can be met is now limited to 1.19 pu. Table-2 shows the revised minimum and maximum power generation limits of each generator. The capacities of DG and FC are increased just in case the number of BEVs are not enough to handle the load demand. The batteries are not allowed to discharge at a rate higher than 0.7C keeping the health of battery in concern.

Table- I: Plug-in and Plug-out timings considered in this scenario.

	Case-1		Case-2		Case-3	
BEV No	plug-in time (s)	plug-out time (s)	plug-in time (s)	plug-out time (s)	plug-in time (s)	plug-out time (s)
1	0	∞	0	∞	0	∞
2	0	48	0	48	0	48
3	0	∞	0	∞	0	280
4	0	∞	100	360	100	360
5	0	∞	0	∞	0	120

Table- II: Minimum and Maximum limits of power generators considered.

	Previous		Present	
	Minimum	**Maximum**	**Minimum**	**Maximum**
Diesel	0.1	0.2	0.1	0.3
Fuel Cells	0.1	0.2	0.1	0.3
Solar PV	0.26	0.29	0.26	0.29
BEVs	0.3 (@0.2C)	1 (@0.9C)	0.2 (@0.1C)	0.3 (@0.7C)
Total	0.76	1.69	0.66	1.19
Note: All values are in per-units (pu)				

All the generating sources shall participate in the frequency regulation irrespective of their ramp rates. The same frequency regulation command is sent to every generator and all of them shall respond to this signal. LCs at these generators will make the necessary changes in the generation commands.

The load variation cases taken in the previous scenario is not considered here in this scenario but same load (with step and noise) for the following three cases to shift the focus on to BEV availabilities.

1) **Case-1**

Initially, all the BEVs are assumed to be present for frequency regulation. In this case, the owner of BEV no.2 has opted to plug-out the vehicle at time T=48s. Hence at 49th second only four BEVs shall be connected to the grid and the share of power generation of out-going BEV is to be shared by other generators in the system. In Figure 15 the SoCs of the batteries are shown. Since BEVs 1,3,4 and 5 are intact with the system, their SoCs are declining based on the discharge rates (Figure 15(a)). The SoC behaviour of BEV-2 is shown in Figure 15(b). At 49th second, after the vehicle has been plugged out, the SoC remains constant since it is no longer sending its power to the microgrid. The load profile is shown in Figure 16. The noise power considered in this case is 10-2 while the seed value used is 1000. This load profile has high distortions (step changes) so that testing the system under such conditions will reveal the stability and frequency regulation.

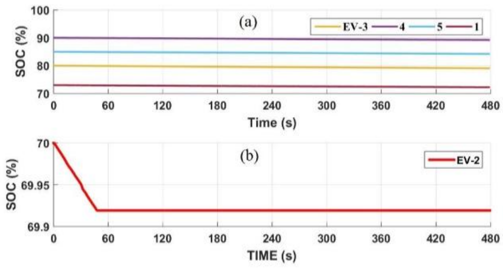

Fig. 16. SoC variation of batteries of EVs

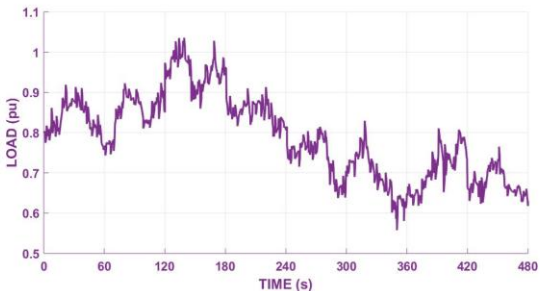

Fig. 17. Actual load signal considered in the system

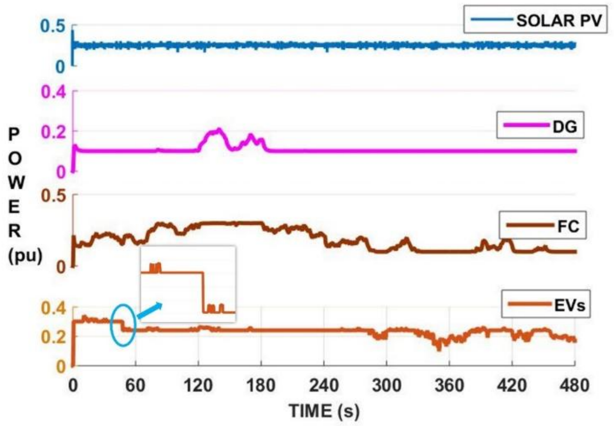

Fig. 18. Active power generation by different sources in the system

With restrictions of power generation in place, the total load is being distributed among the sources and the load sharing is shown in Figure 17. At 48th second, the plugging-out of BEV-2 has caused decrease in power output of EV-fleet (inset). The small shoots in the inset correspond to the frequency regulation command by CC. After 48th second, the share of BEV-2 was taken by FC. At 120th second, there is an increase in the load. BEVs and FC has reached its maximum potential to generate power. Solar PV is also generating at its LPP. So, the excess load is taken up by DG. Due to inertia, there is a slow ramp in the DG response, while the frequency is changing. The proposed algorithm ensures that the frequency error doesnot cross the limits. The frequency response is shown in Figure 18. The simulation is starting from a zero state, hence there is a shoot in the response during initial period.

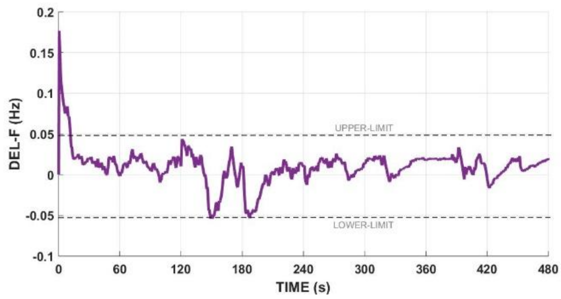

Fig. 19. Frequency change in the system due to load change

2) **Case-2**

Keeping the load profile as mentioned in Figure 16, and the behaviour of BEV-2 intact, it is considered that BEV-4 shall be plugged-in at 100th second and plugged-out at 360th second. Figure 19 shows the power sharing by the sources in the microgrid. At 48th sec, BEV-2 is plugged-out, hence the response is similar to the case-1 considered,ecxept that the pu share is less because BEV-4 is not included in the fleet. At 100th sec, BEV-4 comes into frequency regulation service hence the following observations can be made, (i) there is an increase in the pu load share of the EV-fleet (ii) the load share of FC has decreased and (iii) the DG power output is reduced, since BEVs are given the top priority for discharging power.

In Figure 20, SoC of BEV-4 shows constant value from 0 to 100th sec since it is not connected to the grid and there is no discharging of power.

After 100th sec, the SoC value starts decreasing, based on the discharge rates.

During 360th sec, the pu load is considerably less and hence the EV-fleet load share is less. At this moment, BEV-4 is plugged-out. At 360th sec, once the vehicle is plugged-out, the SoC remains constant there after. The overall power sharing capability of EV-fleet has reduced, since BEV-2 and 4 are plugged-out. FC comes to rescue the system for the increasing load profile after 360th sec.

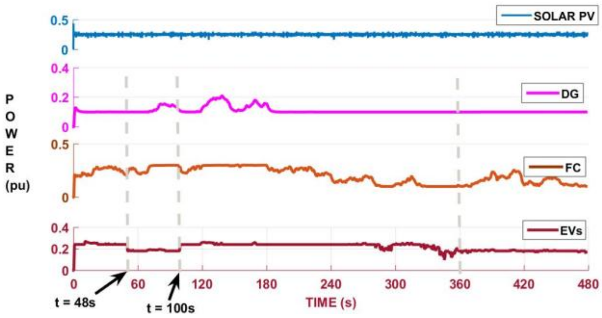

Fig. 20. Active power generation by different sources in the system

The frequency deviation is shown in Figure 21. There is a major disturbance observed after 100th sec, but it can be noted that the deviation of frequency is within the limits of ±0.05 Hz..

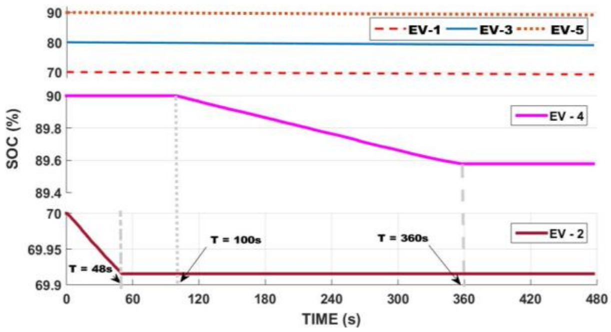

Fig. 21. SoC variation of batteries of EVs with Plug-inand Plug- out times

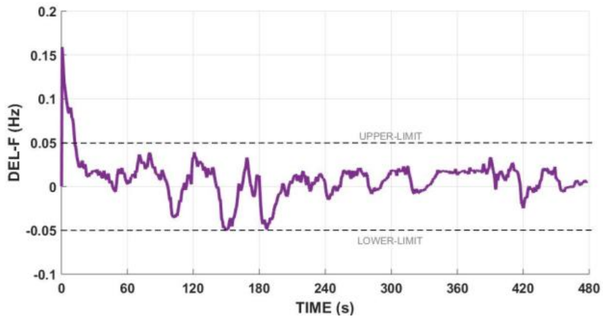

Fig. 22. Frequency change in the system due to load change

3) **Case-3**

In this case, more dynamism is added in the system (in addition to EV-fleet participation), with BEV-3 being plugged-out at 280th sec and BEV-5 plugged-out at 120th sec. The SoC levels of BEV-3 and 5 are shown in Figure 22. They are initially connected to the system, so they participate in the load sharing and hence their SoC has a ramp-down characteristic.

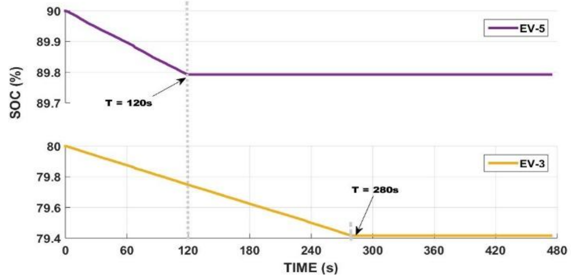

Fig. 23. SoC variation of batteries of EVs with Plug-in and Plug- out times

Figure 23 shows the load sharing by the sources. The events at 48th sec, 100th sec, and 360th sec is discussed in the previous cases. At 120th sec, in the load profile, there is a step load change (increase). It is expected that EV-fleet shall contribute to the extra power share needed by the system. But unfortunately, the owner of BEV-5 has plugged-off the BEV at 120th sec. at this time, FC has also reached its maximum generation value. Hence, the increase in load is dealt by DG. Since there is a decrease in load profile at 280th sec, the loss of power share by EV-3 has not caused much frequency excursion in the system. Figure 24 shows the frequency error profile in the system during the simulation. It can be observed that the frequency deviation is within the acceptable range.

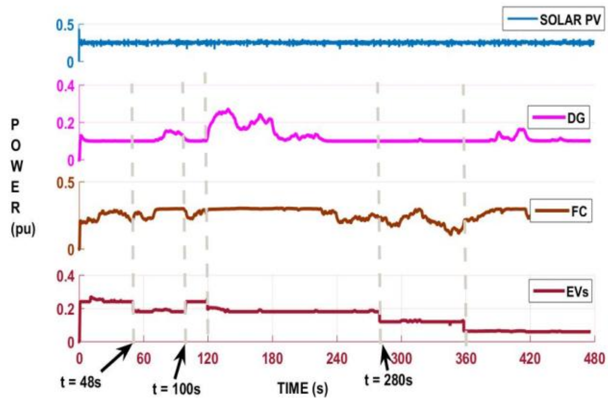

Fig. 24. Active power generation by different sources in the system

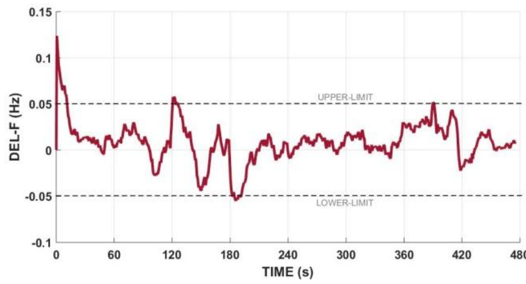

Fig. 25. Frequency change in the system due to load change

VI. ECONOMIC ANALYSIS

The cost benefit of having solar PV as a reserve along with batteries of BEVs makes it economical for the microgrid by avoiding additional investment and maintenance of exclusive batteries for power storage.

An example is considered here for proving the statement. Consider a microgrid with 100KW of peak load,

equivalent to 1.3 pu of load assumed in the paper. A reserve capacity of 10KW would be ideal to deal with the frequency deviations which account to 0.13 pu. Out of 0.13 pu of maximum reserve capacity, solar reserve is considered 0.03 pu equivalent to 2.3kW and the BEVs provide a reserve of 0.1 pu equivalent to 7.3kW. Considering market average installation cost of solar at Rs. 45 per watt, the reserve capacity of the solar would cost Rs. 1,40,000 including installation. The rest of the reserve must come from BEVs powered by Li-ion batteries. Considering that the grid operator gives Rs. 10/kW-h of energy transferred by BEVs, for 7.3 kW the operator shells out Rs. 73 at maximum per day. For ten years, the total spending would be Rs. 2,66,450. If the grid operator has invested in buying a storage battery for the reserve of 9.6 kW, considering a Lead-Acid battery would cost Rs. 3,64,800 (assuming a set of 10, 12V 100Ah batteries). Considering a battery life time of 2 years or 2000 cycles of operation, in 10 years five such batteries are required which costs Rs. 18,24,000. The net spending of Microgrid operator is Rs.4,06,450. The net saving per year is Rs.1,41,755.

VII. CONCLUSION

The adaptive-additive algorithm has been tested on a microgrid with Solar PV, FC, DG and BEV sources under two scenarios. The CC and local controllers have coordinated to make sure that the frequency deviation is not beyond the limits. The results show significant control of the frequency within the error band of ±0.05Hz. BEVs were able to supply the required power to the system during transient and steady state conditions. All the sources could withstand the step and random load changes in the system. The economic viability of the proposed model is also proven to be profitable to the grid operator so that this concept can be put into practice. The microgrid can be self-sufficient to operate in a islanded mode with good power quality and have reduced carbon emissions.

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AUTHORS PROFILE

Phani Kumar K.S.V completed his B.Tech in Electrical and Electronics from Anna University and his M.E from S.R.M University Chennai. He is currently working for his Ph.D. in JNT University Hyderabad in the area of Distributed Generation, Optimization techniques and Power Quality, AI techniques. He is currently working as Assistant Professor in CVR College of Engineering, Hyderabad, Telangana, India.

Dr.S.Venkateshwarlu Completed his B.Tech from Sri Venkateshwara University, Tirupati in Electrical & Electronics Engineering, Masters from NIT Warangal with Electrical Machines & Industrial Drives specialization, Kakatiya University and Ph.D. from College of Engineering, Osmania University, Hyderabad in 2011. His areas of interests are Power Electronics, FACTS applications and Power quality. He is currently working as Professor & Head of EEE at CVR College of Engineering, Hyderabad, Telangana, India.