# Frequency Stability in Weak Grids Using Independent Electric Vehicle

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***Abstract*—Electric vehicles (EV), connected to the power grid, serve as distributed load or energy storage. In weak power grids, integration of Electric vehicles as energy storage provides many services such as power quality improvement, effective power control, and frequency regulation. On the other hand, the EV plug-in/off to a weak grid as a distributed load can result in poor power quality issues such as unacceptable frequency deviation. In this paper, a proposed control/operation strategy is presented to improve the frequency stability of a weak grid connected to EVs. It is proposed to use the EV to improve the frequency deviation during the plug-in EV as a distributed load (charging mode) and/or as a storage device (discharging mode).**

**Furthermore, a smart plug off strategy is proposed in order to disconnect the EV from the weak grid without frequency interruption. The proposed system is simulated in Matlab environment and a comparison between the system with and without the proposed Electric vehicles control schemes under different operating conditions is presented. Results prove the effectiveness of the proposed control/operation strategy.**

***Keywords*—weak grid, electric vehicles, power quality, frequency regulation, power response.**

## I. INTRODUCTION

The use of renewable energies and electric vehicles is developing rapidly in recent years. The Plug-in Electric Vehicle (PEV) is a state-of-the-art environment-friendly technology that can be used to increase power consumption efficiently [1].

Usually, weak grids are existing in medium or low voltage feeders in conventional networks. Compared with strong networks, weak networks have lower inertia and higher resistance, as well as typical low-power ratings [2].

EVs can not only participate in peak load power change but also regulate the frequency of the distribution system. Through the active energy transfer between the EV battery and the distribution network controlled by a two-way power electronic converter, the frequency regulation can be achieved locally [3].

Obviously, large-scale loading and unloading will not only lead to shocks to the network but also will have a significant impact on the quality of the electrical grid, network loss and the use of equipment [4]. Inertia in power systems can compensate for imbalances caused by intermittent renewable energy sources or load disturbances. However, it is still difficult to maintain frequency changes within acceptable limits [5].

During such temporary conditions, it is important to reduce frequency fluctuations and restore energy quality to the normal state of the network as soon as possible [6]. There are many solutions for frequency regulation that analyze the Vehicle to Grid (V2G) technique to regulate the frequency of a microgrid (MG)/weak grid with different penetration levels of EVs. Supplementary Frequency Regulation (SFR) is shared with many EVs through V2G-control that considers both the organization of the control center and the state of charge (SOC) levels of battery expected from EV owners in, [7, 8]. In addition, EV has obvious advantages in regulating the frequency of the power system from an economic point of view to reduce the cost of charging/discharging EVs [1, 9-11]**.**

While frequency control in distribution feeders is based on a two-stage bi-directional V2G converter for EV, SOC is ignored, battery health and age are not considered [3], additional electric vehicles are used in frequency regulation service uses for the unidirectional power flow network [7]. Decentralized V2G control method is decided to participate EVs in the frequency control given the power flow rate and the charging requirements of EV customers. Based on the ideal interconnected grid, the SOC battery control strategy maintain effectively the SOC of the EV battery, while EV is involved in regulating frequency in the system [12].

The rest of this paper is organized as follow. Section II presented modeling for the weak grid and EV to participate in frequency regulation. In Section III, the proposed V2G control strategies represented considering both frequency regulation and charging/discharging strategy. In Section IV, simulation and discussion including the effect of different values of inertia on frequency, EV control charging/ discharging are presented. Finally, some conclusions will be drawn in section V.

## II. SYSTEM MODELING

To explore the effects of EV on electric weak grid as presumed for the frequency regulation system, a weak network model and an EV model are necessary.

### *A. Weak Grid Modeling*

The weak grid can be modeled as a generating unit e.g. primary energy source composed of a prime mover and a rotating electrical machine as a generator. In this paper, the low voltage weak grid with a single-generation source is modeled based on simple models of speed governor and diesel/generator set as shown in Fig. 1.

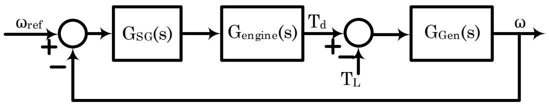

Fig. 1 Block diagram of typical speed loop diesel/generator set based weak grid model

The speed controller transfer function $G_{SG}(s)$ is represented by a PI controller given by:

$$G_{SG}(s) = K_p + \frac{K_i}{s} \tag{1}$$

The overall transfer function of the diesel engine and the generator are given as [5]:

$$G_{engine}(s) = \frac{1}{1+T_{en}s} \tag{2}$$

$$G_{Gen}(s) = \frac{1}{B+Js} \tag{3}$$

Where, $K_P$ is the torque current gain of the speed controller, $T_{en}$ is the engine time constant, $J$ is the inertia of the generator and $B$ is the viscous constant of the generator.

In order to simulate frequency response, the analysis of weak grid can be performed based on the four parameters, $K_P$, $T_{en}$, $J$ and $B$

### *B. Electric Vehicle Modeling*

In weak networks, significant fluctuation in frequency occurs due to inertia response to the energy system as a response to sudden load change. Use of EV can be useful for improving network stability by services frequency regulation and rapid injection of active energy [13]. By enabling fast network activity power, EVs can assist the system operator and improve the impact of system inertia at frequency after disturbance [14]. When system frequency decreases, reducing the EV load or EVs that act as power producers can avoid a greater frequency drop. On the other hand, EV can absorb network energy to avoid a greater increase in frequency [15]. It is possible to separate the control unit of the electric vehicle (EV) by considering the frequency of the system that was detected as the main control signal.

This section proposes a new control scheme for the use of an electric vehicle to regulate the frequency by the rapid injection of energy needed for stabilization while maintaining the independent application of the weak grid as shown in Fig. 2.

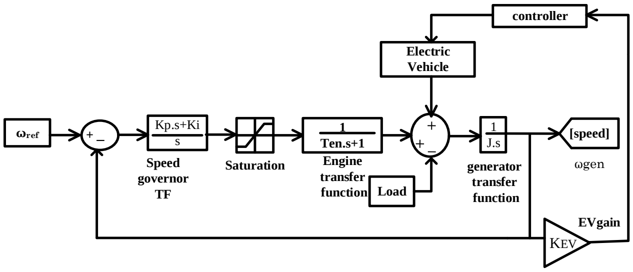

Fig. 2. Speed loop of the frequency with Electric vehicle

Power is provided in the form of a $T_{EV}$ pair to supplement the primary torque while the system meets the charging demand for EV charging that participates in power grid frequency regulation. This technique can be expressed mathematically using a relative gain for $K_{EV}$ as:

$$T_{EV} = K_{EV}\begin{cases} f_{TH}^{1} - f & f < f_{TH}^{1} \\ 0 & f_{TH}^{1} < f < f_{TH}^{h} \\ f - f_{TH}^{h} & f > f_{TH}^{h} \end{cases} \tag{4}$$

The actual operation of the injected power function is the frequency deviation, and the torque resulting from the relative work of the instantaneous frequency deficit appears. The EV controls the frequency and can eliminate the need for communication between the control unit and EV control, This can provide the ability to plug and play the EV control based on EV limited power considering the constraints of battery state of charge (SoC) and charge/discharge power [16].

SoC is the ratio between the rest capacity in the battery and the estimated capacity:

$$SoC = \frac{Q_C}{Q_N} = [Q_N - Q(I_n)]/Q_N \tag{5}$$

Where, $Q_C$ is the power rest of the battery and $Q_N$ is the estimated capacity of the battery.

If the primary state of charging and discharging is $SoC_0$, EV battery SoC can be obtained as [17]:

$$SoC = SoC_0 - \frac{1}{C_N}\int_0^t \eta I dt \tag{6}$$

where, $C_N$ is the rated capacity; $I$ is the battery current, and $\eta$ is the efficiency of charging and discharging. Each vehicle has a specific charging condition that is supposed to be allowed to drop to a minimum of $SoC_{min}$= 0.2, while it can reach a maximum of 0.85 when the EV battery is fully charged. Therefore, SoC should meet the following inequalities: $0.2 \leq SoC \leq 0.85$.

## III. PROPOSED ALGORITHM

The main features of the proposed algorithm are that EV used for frequency regulation PEV is adjusted to the charging and discharge capacity by adjusting the frequency, considering the SoC of EV to withstand the demand for a stable state based on its rated power. In addition, the control algorithm can plug off EV from the system by applying a smart plug off strategy with frequency regulation based on its limited power.

The proposed algorithm includes four main steps:

*Step 1*: select mode of operation for EV charging or discharging after plugging in EV.

*Step 2*: check frequency change within ±1Hz constraint while increasing or decreasing current of EV.

*Step 3*: if frequency change is in the permissible limits, then apply the flow mode of operation, else use the proposed frequency control scheme.

*Step 4*: whenever EV ended its task, apply smart plug off strategy. The plug off strategy is performed in three stages, start with delay five seconds, then reduce the current of the SoC to zero, finally EV becomes ready to exit smooth plug off.

Figure 3 shows the flow chart of the proposed algorithm.

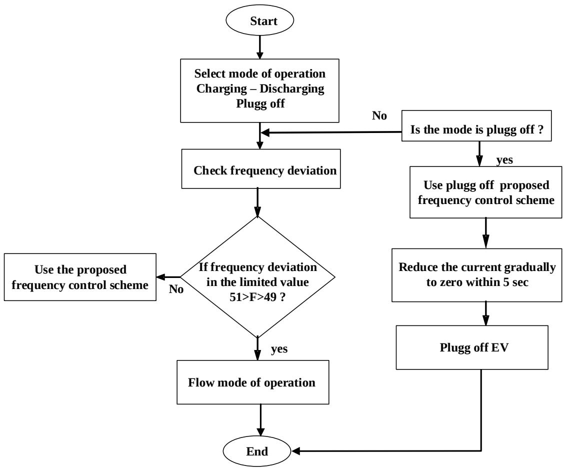

Fig. 3. Flow chart of the proposed algorithm

## IV. SIMULATION AND DISCUSSION

Using the speed model of the weak electrical grid developed in Matlab/Simulink in Fig. 2. The model is able to replicate the effects of a weak low voltage grid fed by a single synchronous generator, developed by consulting an emulation made in an experimental configuration. Subsequently, the model is simulated for a nominal load of 8 kW, which is equivalent to a resistor for each phase of 20 watts in a 230/400 V system, while in fact it depends on the AVR frequency and its operation due to low frequency.

Table I simulated grid model parameters [18]. The simulated responses of the speed seem almost significant in the change of frequency and stability times throughout the transient. To demonstrate the proposed algorithm, the frequency response appears during loading and load shedding before EV connected to the grid as explained by Fig. 4.

Table.I Simulated grid model parameters [18]

| **Parameter** | **Value** |
|---|---|
| Synchronous Generator | 8 kW/10 kVA |
| Synch. Generator Voltage | 230V rms Line- Line |
| Inertia (J) | 0.0447 Kgm$^2$ |
| Engine Time Constant | 35.1 ms |
| Governor speed loop prop. Gain | $K_p$=1 |
| Governor speed loop int. time | Ti=200 ms |
| H | 0.22 s |
| B | 0.0002 Kgm$^2$ rad |
| AVR $K_p$ (PID) | 39.1 |
| AVR $K_i$ (PID) | 142 |
| AVR Kd (PID) | 1.59 |

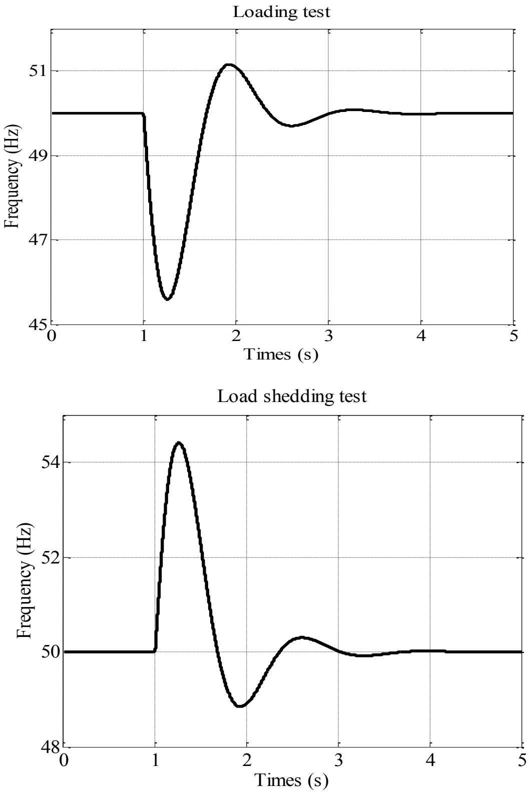

Fig. 4. Frequency response during loading and load shedding.

Figure 4 illustrates that a significant drop in frequency occurs due to the inertia response of the energy system in response to sudden loading and shedding and the frequency exceeded the permissible limits.

### A. *Effect of Changing Inertia*

The system inertia is used to rapidly determine the initial rate of change of frequency whenever a load disturbance occurs [18], [5]. The inertia effect can be observed by simulating the system for different durations with the same change in the load step [13], [19]. Whenever the inertia of the energy system is increased, the speed resulting from load disturbance is decreased and it becomes more resistant. In this case, the frequency deviation is higher due to the low inertia of the weak network.

Figure 5 shows the frequency variations observed for different values of inertia, around the original inertia value [20] while maintaining the parameters of the speed loop remained the same.

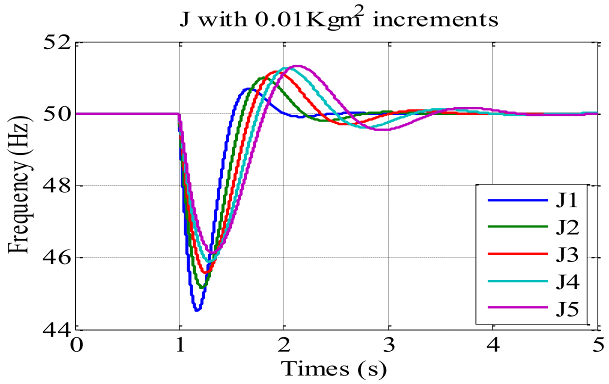

Fig 5. Frequency response for various system inertia

The effect of inertia can be seen in the initial slope after the transient. In addition, it has a significant impact on the maximum frequency drop and maximum time drop. From fig 5. However, increasing inertia did not affect the steady-state frequency due to PI control in the weak grid.

After ascertaining that increased inertia in the weak tested grid, has no beneficial effect in improving the frequency and improving stability, the control system is applied. The proposed control system is tested for frequency stability in the presence of electric vehicles whether for the process of charging or discharging.

### *B. EV and Frequency Regulation*

In order to estimate the performance of the proposed control scheme, many simulation cases are performed. The frequency response is conducted to electric vehicles with an option of control on and off after plugging EV in the weak grid. For this simulation, the speed loop shown in Fig. 2 is used by applying the parameter given in Table 1 with the proportional gain KEV set to 30. The simulation is performed for the weak grid with and without the charging and discharging EV control. Figures 6 and 7 show a comparison between the frequency response when EV plugged in for both charging and discharging with and without applying the independent proposed control algorithm.

When EV is connected to the grid without control at time 5 s, with the load is connected at the 20 s; the frequency crosses both the lower limit (49 Hz), and the upper-frequency limit (51 Hz). The EV control supports and supplies active power as appropriate to the frequency deviation of the restrictions, so that the frequency back to the nominal value.

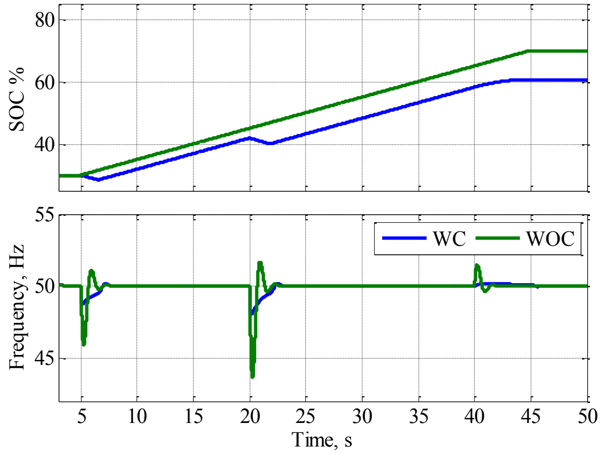

Fig. 6. Frequency response in case of EV charging

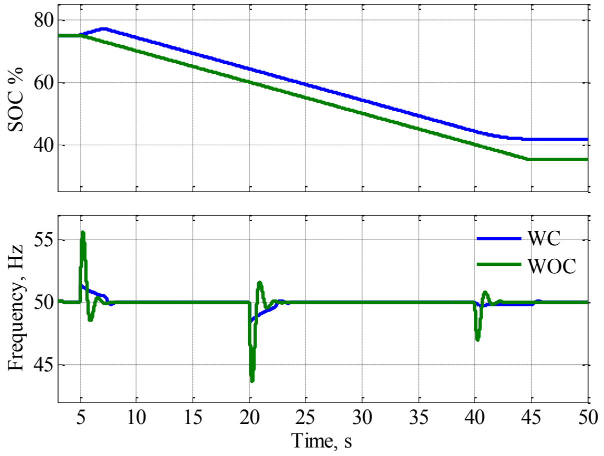

Fig. 7. Frequency response in case of EV discharging

As shown in Figs. 6 and 7, in case that the EV is connected to the grid without the proposed control, EV charging or discharging is continued even after the frequency deviation exceeded the permissible limits. On the other hand, with applying the proposed control method the EV continue charging/discharging until load disturbance occurs then the EV tries to maintain frequency deviation near the permissible constraints based on its rated capacity and then return to the charging/ discharge until it reached the required SoC.

When EV is plugged off without control it cusses a large frequency deviation, but in the presence of smart plug off in the proposed controller, EV is disconnected from the grid smoothly by decreasing current and regulate frequency for stability.

In order to monitor the effects of time delay in frequency detection, the ideal frequency signal is modified by a variable time delay as explained in the next section,

### *C. Effect of Frequency Detection Time Delay*

Time delay control systems can be classified into delay-independent control and delay-based control systems. In stand-alone systems, the time delay does not influence stability. Conversely, in systems that rely on delay, time delay severely affects system stability and lead to instability [21].

PEV is designed by a first-class transfer function, the modified control block schema is illustrated by Fig. 8. As shown in the figure, the first-degree delay of the Td (delay detection frequency) is placed in front of the proportional EV control unit to force the delayed frequency detection effect at the extreme suitable point [16]

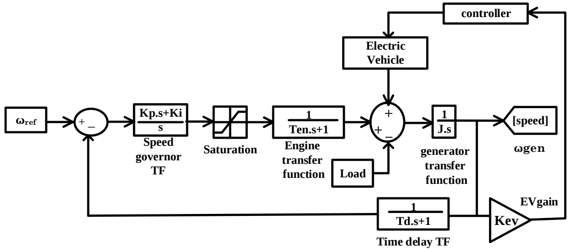

Fig. 8 Block diagram of the proposed ES control system with frequency detection delay

To check the accuracy of the first-order model, the EV model in Fig. 2 is compared with the first order model in Fig. 8 and the results are shown in Fig. 9.

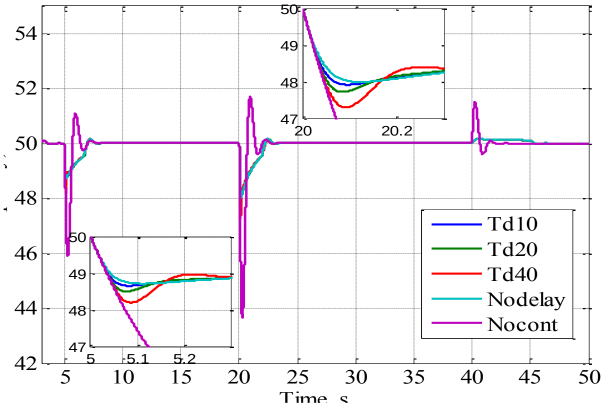

Fig. 9 Frequency regulation with time delay

Figure 9 shows the frequency change obtained during nominal load with EV charging for variable frequency detection delay of 10, 20, and 40 ms. The results show that the first-order approach is adequate for EV modeling for analyzing the charge frequency. According to Fig. 9, when the delay increases, the recovered frequency encounters fewer oscillations with larger first oscillations. However, the time taken by the frequency to settle down to the stability status is almost the same.

## V. CONCLUSION

This paper presented a proposed methodology to reduce the impact of Electric vehicles on weak` grid. The frequency regulation based on the EV control system in a weak grid is investigated. The V2G control strategy was studied with additional frequency regulation. The analysis of the control strategy was proposed in energy programming considering the battery SoC and frequency limits based on the rated power of the EV. The results show that the proposed control strategy can effectively prevent the deviation of the electrical grid frequency during EV charging or discharging that meet the user's demand for the load. The proposed methodology can be expanded to V2G applications for central electric vehicles.

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