Frequency emergency control method considering the plug-in electric vehicles aggregator load shedding

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Abstract. The Plug-In Electric Vehicle (PEV) has fast response characteristics. In this paper, it is used for emergency control of power system frequency in Vehicle to Grid (V2G) mode. The power system frequency dynamics assessment method is given based on PEV aggregator and single machine equivalent model. The PEV aggregator-based system frequency emergency control framework is established, and the main components and scope of the framework are described. A calculation method based on dispatchable PEV load shedding is proposed. The method injects power into the system through V2G mode to balance the Power shortages on the basis of guaranteeing the quality of power system services and the charging demand of PEV users. The simulation results show that the proposed method can cut the load without cutting or under load on the premise of ensuring the target frequency.

1. Introduction
At present, the power system presents two new characteristics: First, the popularization of ultra-high-voltage transmission projects has formed a national large-scale power grid interconnected by various regional power grids [1, 2]; the other is driven by energy saving, emission reduction and clean environment, and the permeability of renewable energy represented by wind energy and solar energy in the system is increasing year by year [3-5]. These two new features lead to two new problems in the system: First, the application of large-capacity ultra-high-voltage AC/DC transmission technology, so that the system will face a power shortage when the large-capacity transmission channel exits due to failure. The second is that renewable energy is mostly connected to the grid through power electronic devices. As the penetration rate of renewable energy increases, the inertia of the system becomes smaller and smaller. The above problem will make the system more likely to have frequency stability problems than ever before.

The number of PEV will continue to grow rapidly in the next 20 years [6-8]. The use of PEV to provide power gap and spin reserve to the system to solve the problem of frequency stability caused by system faults has attracted the interest of relevant researchers. However, from the existing literature, there are very few papers using PEV to participate in the frequency stability control of the system. Literature [9] proposes using distributed intelligent load to participate in the operation and control of the system to deal with the frequency control and its dynamic stability, which provides inspiration and ideas for using PEV to participate in the frequency stability control of the system. Reference [10] uses PEV as a controllable charging load to provide frequency stability support for power systems with renewable energy. However, in the simulation example, only the different numbers of PEV charging loads are disconnected to restore the frequency of the system.
The focus of this paper is on the use of PEV aggregators to participate in the frequency emergency control system. Compared with recent research, there are mainly two differences:

- Based on the aggregator-based V2G conceptual framework, a system frequency emergency control framework was established. The framework is a three-layer structure with a polymerizer as the core, and gives the function and scope of each layer.
- A calculation method for the load shedding of schedulable PEVs is proposed. The method is based on the proposed new idea of frequency emergency control—using PEVs to inject power into the system to balance the active deficiency, considering the energy and capacity constraints of PEVs, and presupposing to ensure the adjustment of service quality and PEVs charging demand.

2. Frequency dynamic evaluation method of considering PEV load shedding

2.1. Single-machine equivalent model with PEV load shedding

Single machine equivalent model is widely used in power system frequency dynamic analysis and low frequency load shedding setting. The single machine equivalent model reflects the overall behavior of the system as a whole when power disturbance occurs.

In this paper, based on the traditional automatic load shedding control (second line of defense) and low frequency load shedding (third line of defense), the PEV load shedding control is added, and the PEV load shedding control is attributed to the second and second safe and stable control of the power system. Road defense line [11]. Since the PEV can be used both as a controllable load and as a power source, the PEV load shedding control includes the charging power control and the discharge power control of the PEV. The single-machine equivalent model of the power system with PEV load shedding is shown in figure 1 [12].

![Figure 1. Single-machine equivalent model of power system with PEV load shedding.](image_url)

In the figure, \( P_{LS1} \), \( P_{LS2} \) and \( P_{LS3} \) are the shear load of PEV, automatic load shedding and low frequency load shedding respectively; \( P_d \) is the magnitude of system disturbance power, which means that the power is lost or the system increases the load when it is negative, and the power generation is increased when it is negative. Loss load; \( P_a \) is the unbalanced power acting on the rotor of a single machine equivalent model.

2.2. Calculation of the load of the single machine equivalent model

The power system is equivalent to a single machine, the load characteristics are neglected, and the control measures such as low frequency load shedding and automatic load shedding are not considered. Assuming that the system disturbance power is a step function, the complex frequency domain expression of the dynamic frequency of the system after the disturbance is as follows:

\[
\left[ -\Delta \omega(s) \frac{1 + T_3 s}{R(1 + T_3 s)(1 + T_3 s)} - \frac{P_d}{s} \right] \frac{1}{Ms + D} = \Delta \omega(s)
\]
Ignore the effect of system damping, and solve the system frequency complex frequency domain expression after perturbation as:

$$\Delta \omega(s) = \frac{P_d}{s} \cdot \frac{T_i T_j R s^2 + (T_i + T_j) R s + R}{M T_i T_j R s^3 + M (T_i + T_j) R s^2 + (M R + T_j) s + 1}$$  \hspace{1cm} (2)$$

Equation (2) establishes a linear relationship between system power shortage and system dynamic frequency by performing single-machine equivalent on the system. As long as the power shortage of the system is determined, the dynamic frequency of the system can be quickly calculated. The calculation of the load shedding amount is as follows: Firstly, the frequency dynamics of the system is evaluated when the power shortage is $P_d$, the system dynamic frequency is calculated quickly, and the automatic load shedding control is performed as needed. It is assumed that the load shedding control is performed at a fixed time (considering the delays such as communication and calculation, assuming that the automatic load shedding action time is a fixed time after the disturbance occurs, such as 150 ms after the disturbance occurs) [13], assuming automatic load shedding action. The time is $t_s$, the load shedding is $P_{ls}$, and the target frequency is the lowest frequency of the system after the load is cut, which is the minimum allowable value of the system, expressed in $\Delta \omega_m$. The equation of motion of the single machine equivalent model with load shedding control is as follows:

$$M \frac{d \Delta \omega}{dt} = \Delta P_m - \left[ \frac{P_d}{s} - \frac{P_{ls}}{s} e^{-s t_s} \right]$$  \hspace{1cm} (3)$$

Where: $U(t - t_s)$ is a step function.

Performing a Laplace transform on equation (3).

$$Ms \Delta \omega(s) = \Delta P_m(s) - \left[ \frac{P_d}{s} - \frac{P_{ls}}{s} e^{-s s} \right]$$  \hspace{1cm} (4)$$

The governor model uses the TGOV1 model, and the complex frequency domain expression of the dynamic frequency in the single-machine equivalent model with automatic load shedding control after active disturbance occurs is

$$\Delta \omega(s) = \left[ \frac{P_d}{s} - \frac{P_{ls}}{s} e^{-s s} \right] \cdot \frac{T_i T_j R s^2 + (T_i + T_j) R s + R}{M T_i T_j R s^3 + M (T_i + T_j) R s^2 + (M R + T_j) s + 1}$$  \hspace{1cm} (5)$$

By calculating the eigenvalue of equation (2), the time domain expression of the dynamic frequency can be calculated. Suppose that the time domain expression of the system frequency after the active deficit is expressed as

$$\Delta \omega(t) = P_d \Delta \omega_1(t)$$  \hspace{1cm} (6)$$

Then the dynamic frequency time domain expression of the system with load shedding control represented by equation (5) is

$$\Delta \omega(t) = P_d \Delta \omega_1(t) - P_{ls} \Delta \omega_1(t - t_s)U(t - t_s)$$  \hspace{1cm} (7)$$

It is difficult to directly calculate the amount of shear load corresponding to the minimum frequency allowable value of the system by equation (7). A cutting load can be set in advance by interpolation, and then the shear load of the system can be obtained by a test method.

3. Frequency emergency control framework based on PEV aggregator

Statistics show that 80% of PEVs have an average driving time of about one hour per day, and the rest of
the time is idle [14]. For idle PEV, under the support of smart grid technology, the fast charge/discharge characteristics of PEV are used to participate in system frequency emergency control. The core idea of PEV participating in system frequency emergency control is to control the charging/discharging behavior of PEV without affecting the normal travel of PEV users, and mobilize as many PEVs as possible to participate in system frequency emergency control to avoid system frequency crash events. Minimize the amount of load shedding and reduce the loss due to load shedding.

Only when the PEV schedulable capacity reaches a certain scale can it participate in the power system frequency emergency control, so the design of the aggregator-based system frequency emergency control framework is necessary. The proposed system frequency emergency control framework is shown in figure 2. The framework is a three-layer control structure centered on the aggregator, the first layer is grid dispatching layer, the second layer is PEV centralized control layer, and the third layer is PEV control layer.

Power grid dispatching layer: The power grid dispatching layer mainly refers to the power grid dispatching center. By performing single-machine equivalent on the system, the system frequency is evaluated online, the lowest value and steady-state value of the frequency dynamic frequency of the system after disturbance are calculated, and the total cut required by the system is determined. The load is transferred to the aggregator with the total load shedding command. At the same time, the grid dispatching center receives the total schedulable PEV capacity of the system transmitted by the aggregator. The fault signal (switching signal) is used to trigger the single-machine equivalent model frequency estimation algorithm of the grid dispatching center.

Centralized control layer of PEV: The function of the centralized control layer of PEV is concentrated in the ACC of the aggregator. It is responsible for collecting relevant load information sent by each PEV substation, determining the total load shedding that the system can schedule, and uploading relevant information to the power grid dispatching center. At the same time, the load shedding command of the power grid dispatching center is accepted, and the load shedding amount required by the system is distributed to the MGAC of the aggregator in each micro network according to the corresponding allocation algorithm.

PEV control layer: The function of the PEV control layer is implemented by the MGAC of the aggregator. It is responsible for collecting relevant information of PEV in the micro-network, including the available quantity of PEV in the micro-network, the initial SOC of the battery, the target SOC, the charging/discharging power of the PEV, the time distribution of the plugged into the charging socket, and the distribution of the charging load of the PEV. According to the collected information and data, MGAC calculates the configurable PEV load shedding amount in the area in real time and uploads it to the ACC. At the same time, it receives and executes the load shedding command given by ACC. According to the corresponding allocation algorithm, the load shedding amount is Distribution between

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Figure 2. Frequency emergency control framework based on PEV aggregator.
4. Calculation method for configurable PEV cutting load

The prerequisite for PEV to participate in system frequency emergency control is that it cannot affect the travel plan of PEV users. Therefore, in the aggregator-controlled PEV, not all PEVs can participate in power system frequency emergency control.

For commuter PEVs, based on economic and convenience considerations, whether the owner or the aggregator will charge the vehicle in the evening. Therefore, it is not feasible to consider the load shedding by stopping the charging of the PEV for most of the day. If PEV is considered to provide energy and ancillary services, then their nighttime charging is also under the management and control of the aggregator, during which time it is not permissible to remove the PEV charging load without the permission of the aggregator [15].

Another problem that must be considered is that the power shortage caused by the system failure is an accidental random event, which allows the aggregator to provide energy and capacity backup for this purpose, which is economically infeasible because the system operator does not An attractive price will be provided to the aggregator for such an alternate.

So a new method of frequency emergency control based on aggregator is proposed in this paper: based on the PEV providing energy and ancillary services, the aggregator injects power into the system through V2G mode on the basis of ensuring the quality of services and the charging demand of PEV users. Balance power shortages and obtain reasonable benefits for frequency emergency control [16-18].

This new idea is mainly to use the fast discharge characteristics of PEV batteries. In the frequency emergency control scheme based on this idea, first consider that the PEV battery injects power into the system through rapid discharge, in order to restore the system power balance as soon as possible. When the schedulable PEV load shedding capacity cannot meet the system requirements, consider using automatic load shedding as a supplement to the PEV load shedding. In the case that the PEV load shedding and the automatic load shedding cannot effectively prevent the system frequency from dropping, the low-frequency load shedding is used as the last line of defense for load shedding control.

The ancillary services herein are represented by the regulation service and assume that the rated charge/discharge power of the PEV n is the same.

At time k, when PEV n provides an upward adjustment service to the system, the power that PEV n can inject into the system is

$$p_E(k) = p_N - p_{RUS}(k)$$

Where: $p_E$ represents the power injected by PEV n into the system; $p_N$ represents the rated charge/discharge power of PEV n.

At time k, when PEV n provides downward adjustment service to the system, PEV n does not inject power into the system in order to ensure the adjustment of service quality and achieve optimal scheduling of the adjustment service.

At time k, when PEV n provides neither the adjustment service nor the charge schedule command of the aggregator, the power injected by the PEV n into the system is

$$p_E(k) = p_N$$

At time k, when the PEV n does not provide the adjustment service, but receives the charging schedule command of the aggregator, in order to ensure the quality of the power service and realize the optimal scheduling of the power service, the PEV n does not inject power into the system.

Obviously, the power injected by PEV n into the system must meet the power constraints of its battery, i.e

$$p_E(k) \leq p_N$$
If there are $N$ PEVs in the aggregator to provide frequency emergency control services, $N_1$ of which are providing upward regulation services, then the power that the aggregator can inject into the system is

$$P_{E_{agg}}(k) = \sum_{n=1}^{N_1} (P_N - P_{RUS}(k)) + \sum_{n=1}^{N-N_1} P_N$$

(11)

Where: $P_{E_{agg}}$ represents the power injected by PEV $n$ into the system.

The above formula needs to satisfy the following inequality

$$P_{E_{agg}}(k) \leq \sum_{n=1}^{N} P_N$$

(12)

Equation (11) does not consider the case where the PEV providing the service leaves early due to various reasons. If the effect of the early departure of the PEV is considered, the power of the aggregator injection system is corrected to

$$P_{E_{agg}}(k) = \left(1 - P_{dep}(k)\right) \left[\sum_{n=1}^{N_1} (P_N - P_{RUS}(k)) + \sum_{n=1}^{N-N_1} P_N\right]$$

(13)

Where: $P_{dep}(k)$ represents the probability that the PEV leaves early at time $k$.

If the power injected into the system by the aggregator represents the PEV shear load in figure 2, the PEV shear load is equal to $-P_{E_{agg}}$. When the aggregator declares to the system the $-P_{E_{agg}}$ that it can provide and obtains the clearing, the system can send a frequency emergency control signal to the aggregator when needed.

The PEV response frequency emergency control signal is affected by the SOC of its battery, except by the rated discharge power of its battery.

The battery capacity of existing PEVs is generally above 50 kWh for pure electric vehicles. Even PHEVs are close to 10 kWh. For example, Toyota’s plug-in hybrid Prius has a battery capacity of 8.8 kWh. In order to reduce the degradation rate of the battery, the lower limit of the SOC is generally set at 10% or more to reduce the depth of discharge of the battery. In the literature [3], the lower limit of the SOC of the PEV battery is set to 20%.

It is assumed that the lower limit value of the SOC of the PEV battery is set to 20%, and the upper limit value is set to 90%. Then for PHEV, the power it can supply to the system is around 2-9 kWh; for BEV, it is at least 10-50 kWh. If there are 100,000 vehicles in the area where the system is located, 50% for hybrid electric vehicles and pure electric vehicles, and the average energy storage of these two vehicles is 5 kWh/vehicle and 20 kWh/vehicle, respectively, they can provide 125 MWh electric energy. With the promotion and popularization of electric vehicles, this data will increase greatly. So for accidental frequency and frequency emergency control with very short duration, so much energy storage is enough. Even if it is not enough, it can be satisfied by automatic load shedding and low frequency load shedding. Therefore, for PEVs participating in frequency emergency control, the SOC is not limited.

5. Simulation

5.1. Test system and relevant data

In order to construct large power gap events, the 9-busbar system of the IEEE 3 Generator given in reference [13] is modified by adding a large-capacity power supply node and an AC line to connect to busbar 8. The purpose is to simulate the external large power grid and large-capacity transmission channels. At the same time, the load of busbar 5, 6 and 8 is added to maintain power balance. In addition, these buses are connected to a certain capacity of PEV, which is managed and dispatched by aggregator. The system wiring diagram is shown in figure 3.
Before and after the change of the 3 machine 9 busbar system, the overall load increased by 50% and 75%. It is assumed that the increased load is entirely borne by the external grid through the transmission line, while ignoring the transmission line losses. The TGOV1 model is used for each generator governor in the test system. The time constants $T_1$, $T_2$, and $T_3$ of each governor are 0.3 seconds, 0.5 seconds, and 1.0 seconds, respectively, ignoring the effect of the governor damping.

Fault setting: The line connected to the external power grid (new AC line) exits due to the fault, resulting in a large power shortage in the test system.

5.2. Simulation results

**Scene 1:** Increase all load bus load in the test system by 50%, and the load change data is shown in table 1.

| Busbar | 5 | 6 | 8 |
|--------|---|---|---|
| Power  | P | Q | P | Q | P | Q |
| Before modification | 125 | 50 | 90 | 30 | 100 | 35 |
| After modification  | 187.5 | 75 | 135 | 45 | 150 | 52.5 |
| PEV    | 25 | 18 | 30 |

It can be seen from table 1 that in scenario 1, the total load of the 3-machine 9 busbar system is increased by 157.5 MW from the 315 MW before the change to 472.5 MW. It is assumed that the increased load is entirely borne by the external power grid through the transmission line, ignoring the transmission line loss, and the newly added power is injected into the system at a power of 157.5 MW.

In table 1, the aggregator can schedule a PEV discharge power of 73 MW. It is assumed here that in the event of a system failure, the maximum capacity (discharge power) of the aggregator for emergency control is 50 MW, and the probability of the PEV leaving early is 5%, so that the emergency control reserve capacity that the aggregator can provide is 47.5 MW. Such an assumption does not affect the impact of the simulation results, because for a frequency emergency control system, it only needs to know how much emergency control backup the aggregator can provide.

The system is equivalent to a single machine, and the dynamic frequency of the system after disturbance is calculated. At the same time, the fault is simulated by PSS/E, and the inertia center frequency of the system is obtained by each generator frequency. The simulation result is shown in figure 4.
It can be seen from figure 4 that the dynamic frequency curve of the single-machine equivalent model is basically consistent with the frequency curve obtained by the PSS/E simulation, indicating that the dynamic frequency evaluation method based on the stand-alone model can accurately describe the frequency dynamic characteristics of the system. The comparison of the simulation results of the two is shown in table 2.

Table 2. Comparison of results between PSS/E and stand-alone equivalent models in scenario 1.

|                | The Lowest frequency (Hz) | Corresponding moment (s) | Steady-state frequency (Hz) |
|----------------|---------------------------|--------------------------|----------------------------|
| PSS/E Simulation | 58.80                     | 1.62                     | 59.12                      |
| Single machine equivalent model | 58.78                     | 1.68                     | 59.10                      |
| Error            | 0.02                      | 0.06                     | 0.02                       |

Assume that the minimum frequency of the system is allowed to be 59 Hz. The minimum system frequency is 58.78 Hz calculated by the stand-alone equivalent model. The automatic load shedding control of the system is required after the fault. The single-machine equivalent model is used to calculate the load shedding. It is assumed that the load-cutting action time is 0.1 s after the fault and the load-cutting load calculation result is 30 MW. The load-cutting amount calculated by the
single-machine equivalent model is all balanced by the rapid discharge of the PEV battery. The simulation is performed using PSS/E, and the system frequency curve and load curve are shown in figure 5 Single machine equivalent model.

The simulation results were analyzed. When the PEV was quickly discharged at 0.1 s, the discharge power was 30 MW. The minimum system frequency curve of the PSS/E simulation was 59.06 Hz, and the frequency error of the control target with 59 Hz was 0.06 Hz. It is particularly important to emphasize that the 59 Hz control target in figure 5 is implemented without changing the system load. Show that: First, The PEV can replace the load to implement the system's frequency emergency control. Second, if the aggregator provides emergency control. The spare capacity is sufficient to ensure continuous power supply to the user in the event of a system failure.

**Scene 2:** In order to simulate a more serious situation, all load bus load in the test system is proportionally increased by 75%, and is borne by the external power supply, and the others are unchanged.

The simulation calculation is carried out using PSS/E and stand-alone equivalent model. The system frequency dynamic curve after fault occurs is shown in figure 6.

![Figure 6. System frequency curve after failure.](image)

|                          | The Lowest frequency (Hz) | Corresponding moment (s) | Steady-state frequency (Hz) |
|--------------------------|---------------------------|--------------------------|----------------------------|
| PSS/E Simulation         | 58.10                     | 1.62                     | 58.65                      |
| Single machine equivalent model | 58.15                     | 1.68                     | 58.635                     |
| Error                    | 0.05                      | 0.06                     | 0.015                      |

It can be seen from figure 6 that when the power shortage reaches 236.75 MW, the dynamic frequency estimation method based on the stand-alone model can still accurately describe the frequency dynamic characteristics of the system. The simulation results of the stand-alone model and PSS/E are shown in table 3.

Assuming that the minimum allowable value of the system is still 59 Hz, the single-machine equivalent model is used to calculate the load shedding. The result of the calculation is that the load is required to be removed by 109 MW. Since the discharge power of PEV can be 47.5 MW, it is necessary to cut off part of the load in the system. The removal load is 61.5 MW. The load shedding
effect is simulated by PSS/E. The dynamic frequency curve of the system after load shedding is shown in figure 7.

![Figure 7](image_url)  
**Figure 7.** System frequency curve and load curve after PEV discharge and load shedding.

From the simulation results, after the PEV discharge and load shedding control, the minimum frequency of the PSS/E simulation system is 59.07 Hz, and the error with the control target 59 Hz is 0.07 Hz. The total system load is reduced from 551.25 MW before the load shedding to 489.75 MW. Show that: Even if the emergency control spare capacity provided by the aggregator is not enough, the load shedding can be reduced on the basis of ensuring the control target, thereby reducing the power outage range and reducing the user's dissatisfaction.

![Figure 8](image_url)  
**Figure 8.** System frequency curve and load curve after the inertia constant is increased.

**Scene 3:** In the frequency dynamic evaluation method based on the single-machine equivalent model of the power system, the inertia constant of the larger-scale power system is larger than that of the small-scale power system. In order to verify that the proposed method is also applicable to large-scale power systems, the inertia constant of the simulation system is doubled, and the remaining operating parameters and fault settings are the same as those of scenario 2. The load shedding was calculated using a stand-alone equivalent model, and the result was a cut-off load of 82 MW. Since the discharge power of PEV can be 47.5 MW, it is necessary to cut off part of the load in the system, and the cutting load is 34.5 MW. The load shedding effect is simulated by PSS/E. The dynamic frequency curve of the system after load shedding is shown in figure 8.

From the simulation results, after the PEV discharge and load shedding control, the minimum
frequency of the PSS/E simulation system is 59.06 Hz, and the error of the control target 59 Hz is 0.06 Hz. The total system load is reduced from 551.25 MW before the load shedding to 516.75 MW. Indicate that: The proposed method is also applicable to large-scale power systems with large inertia constants. Compared to smaller-scale power systems, for the same active vacancy and PEV load shedding, under the premise of ensuring frequency control objectives, larger scale, the power system has a smaller load shedding.

6. Summary

PEV aggregator can be used as power source/storage system to quickly respond to emergency control commands. In this paper, the problem of frequency emergency control based on V2G is preliminary studied. The frequency dynamic assessment method of power system based on single machine model is given. The system frequency emergency control framework is established and the calculation method of dispatchable PEVs load shedding is proposed.

An aggregator with 47.5 MW emergency control reserve capacity was used for the single machine equivalent model of the power system. The simulation results show that the dynamic frequency estimation method based on the single machine model can accurately describe the frequency dynamic characteristics of the system. The PEVs can replace the load to realize the frequency emergency control. Under the premise of ensuring the target frequency, the emergency control reserve capacity provided by the aggregator can avoid or less load shedding to increase the continuity and reliability of the system's power supply.

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