An Optimal Coordinated Method for EVs Participating in Frequency Regulation under Different Power System Operation States

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ABSTRACT This paper proposes an optimal coordinated method for electric vehicles (EVs) participating in frequency regulation (FR) under different power system operation states (PSOSs). In the proposed methodology, the FR power of EVs and generators is coordinated with different optimization objectives for power system secure and economic operations. When a power system operates in normal state, the minimum FR cost is used as an optimization objective considering the battery degradation cost. In the abnormal state, the minimum frequency restoring time is considered in the optimization objective. Based on the optimized results in different scenarios, the output power coordinated control rule between EVs and generators is drawn. Simulations on an interconnected two-area power system have validated the superiority of the proposed optimized coordinated control strategy.

INDEX TERMS Electric vehicles, frequency regulation, operation state, coordinated control, vehicle-to-grid.

I. INTRODUCTION

In order to reduce exhaust emissions and protect environment, many countries encourage renewable energy generation [1]. In the future, renewable energy sources will be massively integrated into power grids and the power system will face serious challenges. Due to the intermittency and uncertainty of renewable energy sources, it is difficult to meet the supply-demand match by only relying on the traditional FR resources [2]. EVs are considered as energy storage devices [3], [4]. Based on vehicle-to-grid (V2G) technology, EVs could charge/discharge from/to power grids [1]. The V2G power in United States, UK, Germany, Italy, etc. may reach 6.8-10 times of their average national load [5], [6], and the number of EVs in the United States has reached 1 million [7]. The increasing number of EVs will bring new opportunities to FR of power system.

There are three ways for EVs participating in FR. The first way is the localized decision-making, for which, each charger determines how much charging/discharging power is based on local information, such as load fluctuations, the arrival time of each EV and the local frequency information [8], [9]. The second way is the decentralized decision-making. In this case, the FR signals are sent to the aggregators by control center for controlling each charging device based on the operating voltage, power loss and so on [6], [10], [11]. The last way is the centralized decision-making. With the support of the communication system, the chargers are controlled by the control center [7], [12].

In the current literature, there are different optimization objectives for EVs participating in FR such as reducing frequency deviation (FD), improving FR revenue and EV owners’ satisfaction [13]-[18]. In order to reduce the FD, the coordinated control strategies of different FR resources are proposed and have better performance [19], [20]. This is because these strategies can utilize the complementarity of different FR resources efficiently. When an operation power system is safe enough, the FR revenue could be improved. The charging/discharging time of EVs could be optimized, for example, EVs charge/discharge from/to grid when the electricity price is low/high [20]-[22]. FR cost reduction, such as reducing the battery degradation cost, also could improve FR revenue [9], [23]. From the EV owners’ point of view, their driving requirements are important and should be
satisfied. Therefore, the state-of-charge (SOC) of EV batteries is necessary to be maximized [24], [25].

The PSOSs could be divided into five states based on the security level [26]-[28]. The optimization objectives of power system depend on the PSOS [29]-[31]. For different optimization objectives, the utilization of each FR resource is different. This is because some characteristics of resources are complementary. For example, the response speed of EVs could reach the millisecond level, the thermal power generators and hydroelectric generators just could reach the seconds level. The response speed of EVs is much faster, but the FR cost of them is higher. In our previous research in [13], the response priorities for EVs participating in FR under different PSOSs are involved. EVs participate in FR under different PSOSs is investigated, but the optimal model is not yet established.

In this paper, an optimal coordinated method for EVs participating in FR under different PSOSs is proposed. In the proposed methodology, the FR power of EVs and generators is coordinated with different optimization objectives for power system secure and economic operations. When a power system operates in normal state, the minimum FR cost is used as an optimization objective considering the battery degradation cost. In the abnormal state, the minimum frequency restoring time is considered in the optimization objective. In simulation, a series of random load and step load are added in the normal state and abnormal state respectively. Based on the proposed optimization method, the coordinated control rule between EVs and generators is drawn. The remainder of this paper is arranged as follows. The optimized model is established in Section II. The particle swarm optimization algorithm and the fuzzy set theory are employed to resolve the optimal model in Section III. In Section IV, the proposed coordinated control strategy between EVs and generators is validated. In Section V, the conclusion is made.

II. PROBLEM FORMULATION

An operation power system should maintain balance between generation and load. Any generation-load mismatch will result in FD. When the system operates in a relatively safe state, the FD is within a certain small range. As the operation power system is divided five states, only normal state is considered relatively safe [27]-[29]. In this paper, the normal state is classified as normal state, and the others are classified as abnormal state.

A. OBJECTIVE FUNCTION

The formulas on FD is adopted from [6], [30], as shown in (1).

\[ \Delta f = \frac{1}{M} \left( \Delta P_{V2G} + \Delta P_{FR} - \Delta P_L - D\Delta f \right) \]  
(1)

\[ \Delta P_{V2G} = \sum_{i=1}^{N} \Delta P_{EV,i} \]  
(2)

where \( \Delta \) denotes the deviation from the initial steady state; \( f \) is the system frequency; \( M \) is the angular momentum; \( P_{V2G} \) is the aggregated V2G power of all EVs; \( P_{FR} \) is the output power of other FR resources; \( P_L \) is the frequency nonsensitive load power; \( D \) is the load-damping coefficient; \( P_{EV,i} \) is the V2G power of the \( i \)th EV; \( N \) is the number of the EVs. In this paper, the EVs are assumed stay in the charging station for the most of time every day. The number of EVs participating in FR could be ensured through incentive measures or policies such as economic incentive. It is similar to demand response (DR). DR is often a cost effective technique that can provide the flexibility required to time shift loads either through prices or incentive policies [21].

The FR cost is formulated as follows:

\[ C_{EV} = C_{deg} + C_{char} + C_{loss} \]  
(3)

\[ C_{EV} = C_{deg} + C_{char} + C_{loss} \]  
(4)

where \( C \) is the FR cost; \( C_{deg} \) is the FR cost of generators; \( C_{EV} \) is the FR cost of EVs, it consists of battery degradation cost \( C_{deg} \), charging cost \( C_{char} \) and power loss cost \( C_{loss} \); \( C_{char} \) is the cost for purchasing/selling the power from/to the power grid; \( C_{loss} \) is the cost for power transmission loss.

The battery degradation cost is result from the charging/discharging of EV batteries and it is calculated as (5) [12].

\[ C_{deg} = \sum_{i \in W} \alpha P_{EV,i}^2 + \sum_{i \in I} \beta \Delta P_{EV,i}^2 \]  
(5)

where \( \alpha \) and \( \beta \) are the model parameters; \( P_{EV,i} \) is the charging power and \( \Delta P_{EV,i} \) is the charging power fluctuation of the \( i \)th EV in interval \( t \); \( W \) is the interval set; \( I \) is the set of EVs; \( P_{EV,i} \) and \( \Delta P_{EV,i} \) could affect battery temperature and active material of battery, they will result in more battery degradation cost.

When a power system operates in a relatively safe state, the FR cost can be considered to reduce. The objective function is shown as follows:

\[
\begin{cases}
\min \{ \Delta f_{max}, \Delta f_{aver}, C \}, S_{state} = 0 \\
\min \{ \Delta f_{max}, \Delta f_{aver}, t_F \}, S_{state} = 1
\end{cases}
\]  
(6)

where \( \Delta f_{max} \) and \( \Delta f_{aver} \) are the maximum and the average FD values during FR process, respectively; \( t_F \) is the time that the FD restores to normal range; \( S_{state} \) is the PSOS, when the system operates in normal state it equals 0, otherwise it equals 1.

B. FR CHARACTERISTICS

1) DYNAMIC CHARACTERISTICS

The dynamic characteristics of generators mainly depend on the time constants of inlet steam chest, reheater and governor. The dynamic characteristics of EVs mainly depend on time constant of battery power adjustment (it can reach up to tens of milliseconds [6], [33]). The response speed and FR accuracy advantages will be obvious if the number of EVs is sufficient. Otherwise the output power of EVs will be restricted by capacity constraint. The output power of the generator is restricted by response speed and ramp rate, compared with that of EVs.

2) COST CHARACTERISTIC

The FR cost of EVs includes battery degradation cost, charging cost and power loss cost. The charging cost is affected by electricity price and charging power, which is expressed as (7). It is a positive number when EVs are charging and a
negative number when EVs are discharging. In this paper, the charging power and discharging power which are provided for FR, are assumed to be equal. If the electricity price for purchasing and selling are also assumed to be equal, the charging cost will be zero. Therefore, the charging cost is not considered in this paper. The power loss cost results from transmission loss and is reflected in charging/discharging efficiency, which is shown in (14) and (15).

\[
C_{\text{EV-charge}} = \sum_{i=1}^{t} \sum_{j=1}^{t} \left( P_{\text{charge},i} - P_{\text{charge},i} \right)
\]

where \( P_{\text{charge},i} \) and \( P_{\text{discharge},i} \) are the charging power and discharging power of the \( i \)th EV in interval \( t \) respectively; \( Z_{\text{purchase},i} \) and \( Z_{\text{sell},i} \) are the electricity price for purchasing power from grid and selling power to grid in interval \( t \) respectively.

EV battery has limited cycle life because of the fading of active materials caused by the charging and discharging cycles [36]. This cycle aging is caused by the growth of cracks in the active materials, a process similar to fatigue in materials subjected to cyclic mechanical loading [36], [37]. The influence factors can be summarized as ambient temperature, cycle depth, charging/discharging power and so on. In [12], [36] and [39], the variable of battery degradation cost equations is V2G power. It could be presumed that the equations are established for the ideal operating conditions (for example, the ambient temperature is 25°C). The relationships between battery degradation cost and V2G power are shown in Fig. 1. The Model 1, Model 2 and Model 3 are battery degradation costs which are calculated based on [12], [36] and [38], respectively. In Model 2, the cost function is a piecewise function, the V2G power in each segment is random. In Model 3, the correlation parameters are the average values. In order to simplify the cost calculation, the cost equation of Model 1 is applied in this paper.

The battery degradation cost, which is shown as (5), is related to the total and the fluctuation of output power of EVs during \( t \). Over-charging/discharging or over-frequent charging/discharging will shorten service life of the battery. The battery degradation cost is illustrated in Fig. 2, in which charging power indicates FR power of EVs within time \( t \). It can be seen that the more EVs participate in FR, the lower battery degradation cost is. In Fig. 2, battery capacity limit is not considered, and it is assumed that the charging power of each EV is the same no matter how many EVs participate in FR.

\[
C_n = \sum_{g=1}^{G} \sum_{i=1}^{N} C_{gi} + \sum_{g=1}^{G} \sum_{t=1}^{T} q_{pr,gt} t_{pr,gt}
\]

where \( C_{gi} \) is the running generation cost of the \( g \)th generator during time period \( t \); \( t \) is the start time of the generator participating in FR; \( t_e \) is the end time of the generator participating in FR; \( u_{gi} \) equals to 1 if the \( g \)th generator is on during time period \( t \) and 0 if not; \( C_{fix,gt} \) is the \( g \)th generator fixed generation cost during \( t \); \( a \) and \( b \) are the generation cost parameters; \( G_{gi} \) is scheduled generation of the \( g \)th generator in the pre-contingency state during \( t \); \( q_{pr,gt} \) is the \( g \)th generator primary reserve rate during \( t \); \( r_{pr,gt} \) is scheduled primary reserve of the \( g \)th generator during \( t \). As can be seen from (8), FR cost of generators is related to output power, generator number and reserve capacity.

**C. CONSTRAINTS**

1) **SOCs of EVs**

When EVs participate in FR, the SOC should be considered. It affects the charging/discharging capacity of each EV.

\[
SOC_{\text{min}} \leq SOC_{\text{int}} \leq SOC_{\text{max}}
\]

\[
E_{t,j} = (SOC_{\text{max}} - SOC_{\text{int}}) E_{0,j}
\]

\[
E_{t,j} = (SOC_{\text{int}} - SOC_{\text{min}}) E_{0,j}
\]

where \( SOC_{\text{max}} \) and \( SOC_{\text{min}} \) are the maximum and minimum SOC of the EVs respectively; These settings are used for avoiding the batteries over-charging/discharging; \( SOC_{\text{int}} \) is the initial SOC of the \( i \)th EV; \( E_{0,j} \) is the energy of the \( j \)th EV for charging; \( E_{0,j} \) is the energy of the \( j \)th EV for discharging; \( E_{0,j} \) is the rated capacity of the \( j \)th EV battery.

2) **Generator Power Output**

In order to avoid the output power of generators is too large or too small, the constraint is shown as (12).

\[
\Delta P_{\text{min},g} \leq \Delta P_{\text{max},g} \leq \Delta P_{\text{max},g}
\]

where \( \Delta P_{\text{min},g} \) is the minimum output power of the \( g \)th generator participating in FR and \( \Delta P_{\text{max},g} \) is the maximum output power of the \( g \)th generator.

3) **EV Charging/Discharging Power**

As the output power of generators, the constraints for output power of EVs can be expressed as follows:

\[
\Delta P_{\text{max},D,i} \leq \Delta P_{\text{V2GD},i} \leq \Delta P_{\text{max},C,i}
\]

\[
\Delta P_{\text{V2GD},i} = \kappa \cdot K_{\text{down}} \cdot P_{\text{V2GD},i}
\]

\[
\Delta P_{\text{V2GC},i} = \zeta \cdot K_{\text{up}} \cdot \Delta P_{\text{V2GC},i}
\]

\[
P_{\text{st,down}} \leq \sum_{t=1}^{T} \Delta P_{\text{V2GD},i} \leq P_{\text{st,up}}
\]

where \( \Delta P_{\text{max},D,i} \) is the maximum discharging power of the \( i \)th EV during time period \( t \); \( \Delta P_{\text{max},C,i} \) is the maximum charging power of the \( i \)th EV during time period \( t \); \( \Delta P_{\text{V2GD},i} \) and \( \Delta P_{\text{V2GC},i} \) are actual discharging power and charging power of the \( i \)th EV; \( \zeta \) and \( \kappa \) are the transmission loss efficiency.
coefficients. They are both less than 1. $K_{\text{Down}}^{i,k}$ and $K_{\text{Up}}^{i,k}$ are the discharging efficiency and charging efficiency coefficients, respectively; $\Delta P_{\text{V2GD}}$ and $\Delta P_{\text{V2GC}}$ are the discharging and charging power of the $i$th EV; $P_{\text{Down}}^{i,k}$ and $P_{\text{Up}}^{i,k}$ are the lower and upper limit capacity of the $i$th charging station, respectively. $N_{\text{EV}}$ is the number of EVs stay in charging station. $\Delta P_{\text{V2GD}}$ and $\Delta P_{\text{V2GC}}$ are vary with the SOC of the $i$th EV, which is formulated as (17) - (20) and shown as Fig. 3 [14].

$$
\begin{align}
K_{\text{Down}}^{i,k} &= 1, \quad \text{SOC}_{i,k} \leq \text{SOC}_{\text{min}}^{i} \quad (17) \\
K_{\text{Up}}^{i,k} &= 0, \quad \text{SOC}_{i,k} > \text{SOC}_{\text{max}}^{i} \\
K_{\text{Down}}^{i,k} &= 0, \quad \text{SOC}_{i,k} > \text{SOC}_{\text{max}}^{i} \\
K_{\text{Up}}^{i,k} &= 1, \quad \text{SOC}_{i,k} \leq \text{SOC}_{\text{min}}^{i} \\
\end{align}
$$

$$
\begin{align}
K_{\text{Down}}^{i,k} &= \frac{1}{2} \left( 1 + \frac{\text{SOC}_{i,k} - \text{SOC}_{\text{min}}^{i}}{\text{SOC}_{\text{max}}^{i} - \text{SOC}_{\text{min}}^{i}} \right), \quad \text{SOC}_{\text{min}}^{i} \leq \text{SOC}_{i,k} \leq \text{SOC}_{\text{max}}^{i} \\
K_{\text{Up}}^{i,k} &= \frac{1}{2} \left( 1 - \frac{\text{SOC}_{i,k} - \text{SOC}_{\text{min}}^{i}}{\text{SOC}_{\text{max}}^{i} - \text{SOC}_{\text{min}}^{i}} \right), \quad \text{SOC}_{\text{min}}^{i} \leq \text{SOC}_{i,k} \leq \text{SOC}_{\text{max}}^{i} \\
\end{align}
$$

$$
\begin{align}
K_{\text{Down}}^{i,k} &= \frac{1}{2} \left( 1 - \frac{\text{SOC}_{i,k} - \text{SOC}_{\text{max}}^{i}}{\text{SOC}_{\text{max}}^{i} - \text{SOC}_{\text{min}}^{i}} \right), \quad \text{SOC}_{\text{max}}^{i} \leq \text{SOC}_{i,k} \leq \text{SOC}_{\text{max}}^{i} \\
K_{\text{Up}}^{i,k} &= \frac{1}{2} \left( 1 + \frac{\text{SOC}_{i,k} - \text{SOC}_{\text{max}}^{i}}{\text{SOC}_{\text{max}}^{i} - \text{SOC}_{\text{min}}^{i}} \right), \quad \text{SOC}_{\text{min}}^{i} \leq \text{SOC}_{i,k} \leq \text{SOC}_{\text{max}}^{i} \\
\end{align}
$$

(20)

where $\text{SOC}_{\text{max}}^{i}$ is the maximum SOC of the $i$th EV; $\text{SOC}_{\text{min}}^{i}$ is the minimum SOC of the $i$th EV; $\text{SOC}_{i,k}$ is the initial SOC of the $i$th EV at plug-in time.

III. OPTIMIZATION ALGORITHM

After the comparison among particle swarm optimization (PSO) algorithm, genetic algorithm (GA) and evolutionary
algorithms (EAS), the optimization result of PSO is overall best. In this paper, the PSO algorithm is chosen. The fuzzy set theory is employed in this paper to find the best compromise solution. The solution procedures are shown as (21) and (22) [34]. The $\theta$th objective function of a solution in the set $F_\theta$ is represented by a membership function $\mu_\theta$. The flow chart of the optimization procedures is shown in Fig. 4.

$$\mu_\theta = \begin{cases} 1, & |F_\theta| \leq |F_\delta|_{\text{min}} \\ \frac{|F_\delta|_{\text{max}} - |F_\theta|}{|F_\delta|_{\text{max}} - |F_\delta|_{\text{min}}}, & |F_\delta|_{\text{min}} < |F_\theta| < |F_\delta|_{\text{max}} \\ 0, & |F_\theta| \geq |F_\delta|_{\text{max}} \end{cases}$$

(21)

$$\mu^0 = \frac{\sum_{\delta=1}^{N_h} \xi_\delta \mu^0_\delta}{\sum_{\delta=1}^{N_h} \xi_\delta}$$

(22)

where $|F_\delta|_{\text{max}}$ and $|F_\delta|_{\text{min}}$ are the maximum and minimum value of the $\theta$th objective function respectively. For each solution $\theta$, the normalized membership function $\mu^0_\delta$ is calculated as (22). $H$ is the number of solutions. The best compromise solution is the one with the maximum $\mu^0_\delta$. $\xi_\delta$ is the weight coefficient of the $\theta$th objective function.

### IV. SIMULATIONS AND RESULTS

In this paper, the proposed approach is an off-line optimization to determine the optimal coordinated control strategy for EVs and generators participating in FR. The off-line optimization process should be implemented with a great variety of load disturbances to experience enough power system scenarios in a high-accuracy simulation environment, and numerous explorations with EV charging/discharging strategies should be sampled sufficiently in various system operation states. Consequently, the optimized control strategy can then be implemented on-site operation, and the optimal charging/discharging power for each EV can be obtained to meet the timeliness requirement based on the current system operation state.

The simulation model based on MATLAB/Simulink is shown as Fig. 5. The FR resources of both area A and area B include generators and EVs. The model parameters of the two-area interconnected system are taken from [6] and [13], as shown in Table I-III. The FR signal is based on the area control error (ACE) under the TBC control mode, as follows,

$$ACE = \Delta P_{tie} + BAf$$

(23)

In order to simulate the load fluctuation in normal state, a series of random load, which fluctuates within a certain range, is added in area A and area B. As the unit of the parameters in Table IV is hour, the random fluctuation time of the load in normal state is set to 1 hour. Two step loads are added in area A and area B respectively, for simulating the disturbed load in abnormal state of power system, one is -0.8MW the other is $P_{abnormal}$.

![Block diagram of FR for two areas with generators and EV charging stations](image)

**FIGURE 5.** Block diagram of FR for two areas with generators and EV charging stations

<table>
<thead>
<tr>
<th>TABLE I PARAMETERS OF THE SIMULATION SYSTEM MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>System base (MW)</td>
</tr>
<tr>
<td>$T_{ch}$, $T_{ro}$ (sec)</td>
</tr>
<tr>
<td>$T_{ch}$, $T_{ro}$ (sec)</td>
</tr>
<tr>
<td>$T_{align}$, $T_{lhb}$ (sec)</td>
</tr>
<tr>
<td>$M_a$, $M_b$ (MW/HHz)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE II PARAMETERS OF THE EV CHARGING STATION MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>EV frequency characteristic coefficient, $k_{v,\text{opt}}$, $k_{v,\text{opt}}$ (MW/HHz)</td>
</tr>
<tr>
<td>EV battery gain, $k_{ev,\text{opt}}$, $k_{ev,\text{opt}}$</td>
</tr>
<tr>
<td>EV battery filter time constant, $T_{ch}$, $T_{ch}$ (sec)</td>
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<tr>
<td>1st order delay of DC/AC inverter, $T_{ch}$, $T_{ch}$ (sec)</td>
</tr>
<tr>
<td>The number of EVs in area A</td>
</tr>
<tr>
<td>The number of EVs in area B</td>
</tr>
<tr>
<td>The number of generators in area A</td>
</tr>
<tr>
<td>The number of generators in area B</td>
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</tbody>
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<tr>
<th>TABLE III PARAMETERS OF EVS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
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<tr>
<td>$S_{SOC}$</td>
</tr>
<tr>
<td>$SOC_{max}$</td>
</tr>
<tr>
<td>$SOC_{ld}$</td>
</tr>
<tr>
<td>Battery capacity (kWh)</td>
</tr>
<tr>
<td>$\Delta P_{max,L}$</td>
</tr>
<tr>
<td>$\Delta P_{max,C}$</td>
</tr>
<tr>
<td>$\kappa$</td>
</tr>
<tr>
<td>$\zeta$</td>
</tr>
<tr>
<td>$\alpha$</td>
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<table>
<thead>
<tr>
<th>TABLE IV THE FR COST PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>Cost of CH ($/h)$</td>
</tr>
<tr>
<td>$\omega_{EV}$ ($$/MWh$$)</td>
</tr>
<tr>
<td>$b_i$ ($$/MWh$$)</td>
</tr>
<tr>
<td>$\eta_{EV}$ ($$/MWh$$)</td>
</tr>
<tr>
<td>$\beta$ ($$/MWh$$)</td>
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<td>$\eta_{EV}$ ($$/MWh$$)</td>
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<td>$\eta_{EV}$ ($$/MWh$$)</td>
</tr>
</tbody>
</table>
1) NORMAL STATE
As shown in Fig. 6 and Fig. 7, the sum of output power of EVs and generators in normal state fluctuates significantly because of the random loads. The sum output power of EVs and generators in normal state trends to increase with the increase of $P_{\text{normal}}$. The sum output power of EVs is small, and the output power at each moment can be negligible.

2) ABNORMAL STATE
In the abnormal state, the operation power system is not safe. In order to make the FD restore to the normal range as soon as possible, the complementary of EVs and generators should be utilized. As shown in Fig. 8 and Fig. 9, in abnormal state, the output power of generators increases with the increase of $P_{\text{abnormal}}$, and the output power of EVs is always the maximum. The output power is the final stable value. In abnormal state, the optimized effect of any of these three objectives is the same, the minimum FD. Therefore, the output power has no rule with the $\xi_{\text{abnormal}}$.

![Figure 6: The sum output power of EVs under different scenarios in normal state](image)

![Figure 7: The sum output power of generators under different scenarios in normal state](image)

![Figure 8: The output power of EVs under different scenarios of abnormal state](image)

![Figure 9: The output power of generators under different scenarios of abnormal state](image)

B. SIMULATION AND DISCUSSION
The FR strategy, which is shown in area A of Fig. 5, is named STRATEGY1. As shown in [13], the FR control strategy is named STRATEGY2. In STRATEGY2, the response priorities and control strategies for the FRRs vary with different operating states. The FR control strategy optimized by the proposed optimization method, which is shown in Table V, is named STRATEGY3. In STRATEGY3, the number of EVs is increased to two times, is named STRATEGY3+.

In order to evaluate the effectiveness of the FR control strategies, the different indicators in different states are calculated and listed in Tables VI.

1) NORMAL STATE

![Table V: The coordinated control strategy 3](image)
generators participate in FR. In STRATEGY3, only the generators undertake the FR task. In STRATEGY3, the output power of generators is the least.

Tie-line power of different control strategies is shown in Fig. 12. In STRATEGY3, the tie-line power fluctuation is more dramatic than STRATEGY1 and STRATEGY2. This is because the FR power in STRATEGY3 is the least.

The FD of different coordinated control strategies is shown in Fig. 13. The FR power in STRATEGY3 is the least. However, the FD of STRATEGY3 is a little less than other strategies. As shown in Table VI, the FR effect of STRATEGY3 is the best, and the FR cost is much less than other strategies. This is because the random load fluctuates constantly. The FR cost of STRATEGY2 is less than that of STRATEGY2. This is because the output power of generators in STRATEGY3 is the less. The FR result of STRATEGY3+ is the same with STRATEGY3, this is because EVs do not participate in FR.

A -0.8MW load and an 1.6MW load are added in area A at the 10th second and area B at the 15th second respectively. The output power of different strategies is shown as Fig. 14. In STRATEGY2, EVs participate FR when the ACE reaches response thresholds. In STRATEGY3, the output power of EVs response faster than STRATEGY1 and STRATEGY2.

The tie-line power and FD of different strategies are shown in Fig. 15 and Fig. 16 respectively. As shown in Table VI, the performance of STRATEGY3 is the best, and the performance of STRATEGY3+ is better than STRATEGY3 because that there are more EVs participating in FR and more quick response power. The performance of STRATEGY3+ is a little better because of the capacity constraint of EVs.
Based on the optimized results, the output power of generators is appropriately less and the output power of EVs is as less as possible in normal state, and the output power of EVs is as much as possible and the remainder of the FR power is the output power of generators in abnormal state.

![Graph showing frequency deviation](image)

**TABLE VI SIMULATION RESULTS OF DIFFERENT METHODS**

<table>
<thead>
<tr>
<th>STRATEGY</th>
<th>STRATEGY1</th>
<th>STRATEGY2</th>
<th>STRATEGY3</th>
<th>STRATEGY3+</th>
</tr>
</thead>
<tbody>
<tr>
<td>The normal state</td>
<td>0.0552</td>
<td>0.0542</td>
<td>0.0549</td>
<td>0.0549</td>
</tr>
<tr>
<td>The average FD (Hz)</td>
<td>0.0120</td>
<td>0.0122</td>
<td>0.0106</td>
<td>0.0106</td>
</tr>
<tr>
<td>The FR cost of generators ($)</td>
<td>276.1746</td>
<td>211.3497</td>
<td>231.0159</td>
<td>231.0159</td>
</tr>
<tr>
<td>The FR cost of EVs ($)</td>
<td>541.3750</td>
<td>485.6162</td>
<td>0</td>
<td>0</td>
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<tr>
<td>The total cost ($)</td>
<td>817.5496</td>
<td>696.9659</td>
<td>231.0159</td>
<td>231.0159</td>
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<tr>
<td>The abnormal state</td>
<td>0.9557</td>
<td>0.9352</td>
<td>0.9347</td>
<td>0.9346</td>
</tr>
<tr>
<td>The maximum FD (Hz)</td>
<td>0.0134</td>
<td>0.0134</td>
<td>0.0096</td>
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<tr>
<td>The average FD (Hz)</td>
<td>85.1717</td>
<td>85.1716</td>
<td>42.9876</td>
<td>42.9874</td>
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<tr>
<td>The recovery time (s)</td>
<td></td>
<td></td>
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**FIGURE 16.** The FD response of EVs and generators in abnormal state.

**FIGURE 17.** The output powers for different SOC EVs in abnormal state.

V. CONCLUSION

In this paper, an optimal coordinated method for EVs participating in FR under different PSOSs is proposed. In the proposed methodology, the complementarity of EVs and generators under different PSOSs is utilized. In normal state, the power system is relatively safe, while in the abnormal state, the FD must be restored to normal range as soon as possible. When a power system operates in normal state, the minimum FR cost is used as an optimization objective considering the battery degradation cost. In the abnormal state, the minimum frequency restoration time is considered in the optimization objective. In this paper, the FR cost of EVs is higher but the response speed is more rapidly. In the simulation examples, a series of random load in an hour and step load are added as disturbed loads. Based on the optimized results in different scenarios, the optimal coordinated control rule between EVs and generators is drawn. The output power of EVs and generators is suggested to be less in normal state and the output power of EVs is suggested to be more in abnormal state. The simulation results have proved that the FR cost is reduced in normal state and the frequency recovery time and the FD are improved in abnormal state with the proposed coordinated method.

REFERENCES


