UTILIZING LOCAL RESOURCES TO PARTICIPATE IN POWER BALANCE: A CONCEPT AND ITS REALIZATION

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ABSTRACT

Integrating large amount of low-inertia and intermittent renewable generation into the power system has increased the occurrence probability of power system imbalance brought about by large disturbances in short time scale and reduced the control capability of the power system under those disturbances. The continually increased electric vehicles(EVs) connected to the power grid may be capable of responding to those disturbances and contributed to the power balance by utilizing the fast-response, continuously regulating and power decoupling control capability of the power electronic charging interfaces. In this paper, different control schemes have been proposed to respond to the disturbances originated from distribution systems and the transmission systems respectively by regarding the electric vehicles as power support resources and considering the characteristics of the distribution network. A typical 11-kV 38-node system has been presented and tested to validate the effectiveness of utilizing the electric vehicles as power balance control resources and the related control schemes.

INTRODUCTION

Integrating large amount of renewable generation into the distribution network by distributed generation or the transmission network by large-scale generation intends to reduce the reliance on fossil fuels and the carbon emission. However, due to the rapidly varying renewable generation, the power imbalance seems to rise both in the magnitude and times which may lead to active power disturbances threating the safe operation of the power system [1]. In the primary frequency regulation stage, instead of dealing with those disturbances with spinning reserve provided by the fossil fuelled generators which may cause air pollution and economic concerns, to balance as much as active power at the distribution level under those dangerous situations with the local resources including the adjustable load and the fast developing vehicle electrification may be adopted as an alternative way. This paper focuses on utilizing the electric vehicles (EVs) to solve the power imbalance issues caused by large disturbances in short time scale in consideration of regulation requirements and the distribution network characteristics. The disturbances are divided into the distribution-level disturbances and the transmission-level disturbances respectively.

In the following parts of the paper, the regulation constrains including the EV related ones and the distribution network related ones are illustrated in Section II. Section III presents the charging and discharging control strategies including the control procedures and the algorithm. At last an 11-kV 38-node system was used to simulate the realization of the provided charging and discharging control strategies.

REGULATION CONSTRAINTS

EV parameters and driving pattern constraints

Based on the conclusions that overall EV transportation system cost can be reduced by providing rich charging infrastructure rather than compensating for lean infrastructure with additional battery size drawn in reference [2] in the present economic and technological conditions, this paper assumes that the charging stations have been widely configured which contributed to the reduction in battery capacity in each EV and the realization of the V2G (vehicle to grid) concept. The number of electric vehicles that is available for regulation is constrained by the daily driving pattern in the aspects of the time randomness and the space randomness. The time randomness refers to the time that each EV connects or disconnects from the gird while the space randomness refers to the connection points in the distribution network. The exchanging power constraints between each EV and the grid can be expressed as

$$P_g^c = P_b^c / \eta_1 \tag{1}$$

$$P_g^{dc} = P_b^{dc} * \eta_2 \tag{2}$$

where $P_b{}^c$ and$P_b{}^{dc}$ refer to the charging and discharging power in the DC side of the charging station respectively while $P_g{}^c$ and $P_g{}^{dc}$ refer to the charging and discharging power in the AC side of the charging station respectively. And η_1 and η_2 indicate the charging and discharging efficiency.

Distribution network constraints

With the equivalent circuit of distribution illustrated in reference [3], the voltage drop can be approximately expressed as

$$\Delta U = U_1 - U_2 = \frac{PR + QX}{U_2} \tag{3}$$

The meanings of the variables can be found in reference [3].Because that the ratio of resistance(R) and reactor(X) usually locates between 1 and 3 in the distribution network [3], much larger than that in the transmission network, the voltage deviation in the distribution network is strongly correlated with both the active and reactive power as it is shown in the formula above. Thus the distribution system voltage constraints should be considered when scheduling the charging power and regulating the active and reactive power may both contribute to a reasonable system voltage.

CHARING AND DISCHARGING CONTROL STRATEGY

For each power electronic interfaced distributed unit connected to the distribution network, the maximum available reactive power that can be utilized for regulation can be approximately expressed as

$$Q_{\max} = \left| \sqrt{S_N^2 - P^2} \right| \qquad （4）$$

where S_N and P denote the rated capacity and the produced active power of the power electronic devices respectively and Q_{max} refers to the maximum reactive power available for regulation. This paper only considers the potential reactive power compensation capability of the EV charging facilities, without regard to the distributed generation system capabilities, for the wide configuration of those facilities which benefits the control schemes explained below.

The goal of the control strategies is to acquire the optimized active and reactive power support from the charging facilities with regard to the voltage constraints of the distribution network in condition that the power grid incurs distribution-level or transmission-level disturbances. This paper adopts the local control concepts proposed in reference [4] and has constructed the control schemes. By obtaining the node information including the local voltage and the frequency related measurements, the local control algorithm can produce the charging control signals of the same node. The localization of the control process reduces the computation and communication capacity and shortens the signal producing time which is more suitable for the power support in the primary frequency regulation stage. In addition, for this method only dealing with the "local" issues, the wide configuration of the regulation resources is quite essential. The elaborate illustration of the control steps and formulation according to different disturbances will be displayed in the following parts.

Disturbances from distribution system

The disturbances from the distribution system mainly originate from the simultaneous generation shortage of distributed generators and cause the threshold crossing of the voltage. The control process of the charging facilities based on the local control theory is as follows:

Step 1: If abnormal node voltage drop was detected, the maximum available would be sent out by the charging facilities at the node;

Step 2: If the maximum available reactive power has already been sent out and the node voltage is still out of the limitation, the charging power would be proportionally reduced by the predefined value and the reactive power would be increased to the new maximum;

Step 3: If the node voltage does not meet the requirements, the **Step 2** would be repeated until the charging power is reduced to zero and the reactive power is at its maximum value.

Step 4: If the node voltage is still in the unsafe range after the **Step 3**, the EV batteries would be discharged to send the active power back to the distribution system. The discharging power and the related reactive power would be proportionally increased and reduced respectively until the voltage meets the requirements.

What should be noted is that the approximate ratio of R and X is important in determining whether the discharging of the EVs should be adopted. From the formula (3), when the ratio equals to or is smaller than 1, utilizing the reactive power for voltage regulation may have almost the same or even better effects than the active power. Thus in this situation, other regulation resources and methods rather than the discharging of the EVs may have better effects.

Disturbances from transmission system

The disturbances from the transmission system cause the frequency deviation of the whole system which contains a large sum of distribution networks. Thus the local charging control strategies of the EVs during the power system primary frequency regulation are as follows:

Step 1: If abnormal frequency excursion was detected, charging facilities stop charging or send the active power back to the distribution system immediately;

Step 2: If the voltage exceeds the upper limit after the pause of charging or the discharging of the batteries, the node voltage measurements would be fed back to produce the reactive power regulation signals.

The following procedures are similar to those in "Disturbances from distribution system" which may not be elaborately displayed due to the space constraints.

Based on the analysis above, the charging control formulation of the EVs can be expressed as

$$\begin{cases} P_{evi} = n_{step} * P_{stepi} \\ Q_{i\max} = \left| \sqrt{S_{Ni}^2 - P_{evi}^2} \right| \\ Q_{evi} = Q_{i\max} * \Delta V_i / \left| \Delta V_i \right| \end{cases} \qquad （5）$$

where P_{evi} and Q_{evi} are the exchanging active and reactive power between the EVs and the distribution system at node *i* respectively. And P_{stepi} is the regulating step of the charging power at node *i* which can be valued according to the power system requirements and the various disturbances in actual operation.

SIMULATION AND ANALYSIS

The typical British distribution system, 11kV-38node distribution system, was adopted for simulation analysis and the system load can be divided into residential load, industrial load and commercial load. The detailed data of this system can be found in reference [5]. The voltage of distribution system was required to keep between 0.95 and 1.05. Total amount of 850 kW wind generation was connected to node 18 and node 33 respectively. The whole distribution system is illustrated in Fig.1.

The number of vehicles is assumed to be 2840 in the distribution system [5], 30 per cent of which have been supposed to be electrified. Only the typical workday and the private cars are included in the study. The daily load curves and the driving patterns [6]are illustrated in Fig.2. The daily load curves are illustrated in residential, industrial and commercial loads respectively. The daily drive patterns indicate the ratio of the vehicle trips started at the specific hour and the total trips of the day that are expressed in percentage.

By randomly setting each of the EVs with two or three trips per day and assuming that every single travel is completed within one hour, the EVs that are not utilized for transportation can be calculated in each hour. They are supposed to be connected to the grid and ready for regulation in the corresponding hour.

In order to reduce the cost of the charging facilities configuration, the regular British electrical outlets, with the parameter of 13A/230V/50Hz, are applied for the EV recharging and the transfer efficiencies of both the charging and discharging process are assumed to be 0.8. Taking certain reserve power, the rated charging and discharging power at the DC side of the facilities are assumed to be 2.5kW and -2.5kW and the rated apparent power of the charging facilities is supposed to be 3.25MVA. By several simulation trials and considering the fast and precise regulation requirements, the regulating step of the active power is set to be 1.04kW. Random sampling of the possible EV connection nodes has been employed to describe the space randomness. The 1st, 9th and 14th hours have been selected for analysis. For simplification of the analysis, in all the three hours, the scheduled power of the distributed generators is supposed to be 850kW. The distribution level disturbances contain the 50% actual generation of the scheduled generation and the zero generation. The transmission level disturbances are not elaborately described but all the connected EVs are assumed to discharge in response to the disturbances for simplification. The studied hours are as follows:

(1) At the 1st hour, the system load is at its minimum point and the EVs are possibly connected at the residential load nodes;

(2) At the 9th hour, the EVs are connected to the distribution system at the least number, possibly at the all the three kinds of nodes;

(3) At the 14th hour, the sum of industrial load and commercial load is at its maximum point and the EVs are possibly connected at the industrial or the commercial load nodes.

In dealing with the uncertainty in the recharging starting time, this paper adopts the worst situation that in each analysed hour all the EVs connected to the gird are regarded as the charging loads. In each hour, EVs' responses to the different disturbances have been obtained in the form of the exchanging active and reactive power variation between the EVs and the distribution network. Due to the space constraints, only those typical results in each hour are displayed in the following figures.

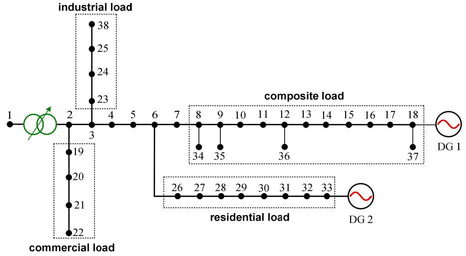

Fig. 1 Modified 11-kv 38-node distribution system

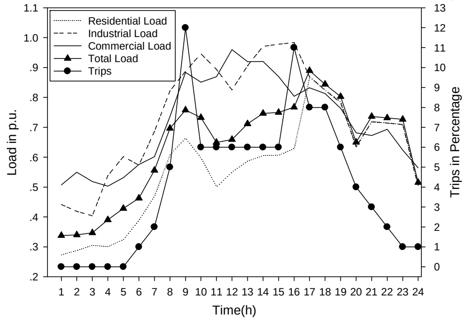

Fig.2 Daily load curve and driven pattern curve

The results of the 1st hour are shown in Fig.3 and Fig.4. When the generation of the DGs decreases to zero, the system voltage violates the lower limit and is not able to recover to the normal level by merely utilizing the available reactive power. Then the charging facilities reduce the charging power by P_{stepi} defined previously and increase the reactive power compensation with the new capacity. The voltage then returns to the normal level. When the transmission-level disturbances occur, the charging facilities start to provide the maximum active power support to the grid and the node voltages violate the upper limit. Through absorbing the reactive power with the residual power capacity in charging facilities, all the node voltages decrease back to the normal level except the node 17 and 18. This is because that there are none EVs connected to those nodes and none local regulation resources.

At the 9th hour and the 14th hour, because of the heavier load, the system voltage is easier to violate the lower limit under the distribution-level disturbances than exceed the upper limit when providing the reverse power to the grid. Therefore only the responses to the distribution-level disturbances are shown in Fig.5, Fig.6 and Fig.7. Comparing those results, the EVs may appear in all nodes at the 9th hour, indicating that the charging control schemes can be performed in the more dispersed range and benefits the local control realization. In Fig.7, the voltages of the nodes numbered from 31 to 33 are still below the lower limit even though the charging control schemes have been performed. This is because that none EVs are connected to these nodes at this time, the same reason to the situation in the 1st hour. These are the disadvantages of the local control. An alternative to solve this problem in the actual operation is to add some new regulation resources or perform the local control within a group of nodes by increasing some communication to obtain the "mutual support".

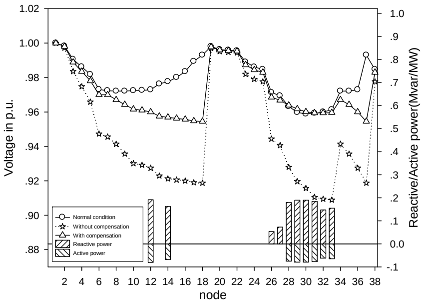

Fig. 3 EV response and system condition after DG output active power reduced by 100% in 1st hour

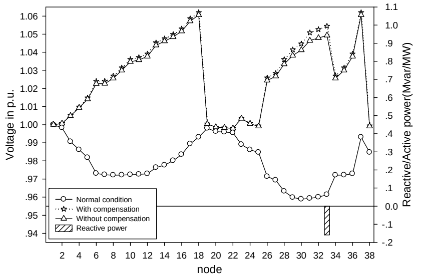

Fig. 4 EV response and system condition after the transmission-level disturbance in 1st hour

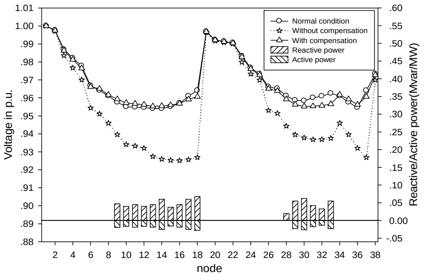

Fig. 5 EV response and system condition after DG output active power reduced by 50% in 9th hour

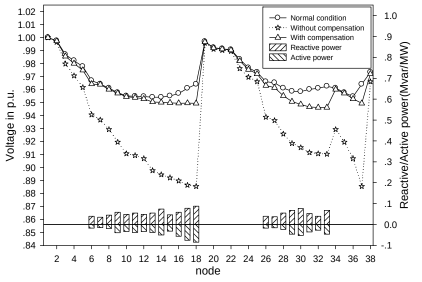

Fig. 6 EV response and system condition after DG output active power reduced by 100% in 9th hour

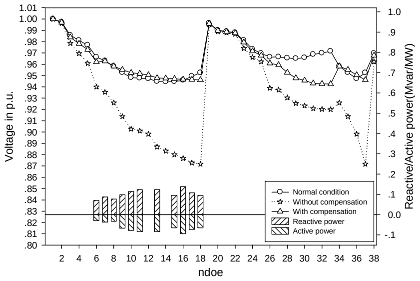

Fig. 7 EV response and system condition after DG output active power reduced by 100% in 14th hour

CONCLUSION

This paper has utilized the charging control of the EVs and adopted the relevant control strategies to respond to the disturbances originated from both the distribution and transmission systems in a short time scale. And the following conclusions have been drawn:

(1)By utilizing the power electronic interfaces of the charging facilities, the local control concepts and the control strategies proposed by this paper, the EVs can be applied in providing power support to the grid without violating the system voltage constraints under the large disturbances in short time scale.

(2)The local control has been validated feasible in the charging control strategies especially when the charging facilities have been widely configured.

(3)The new regulation resources EV and the related control strategies may increase the control capability of the power system which benefits the growing integration of the renewable generation.

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