Frequency Control in Distribution Feeders based on Bidirectional V2G Converter for EV

Ran Wei[1], *Zongjie Liu*[1], *Ke Zhou*[1], *Lei Xu*[1]
1 State Grid Jining Power Supply Company.
Jining, China
weiranshandong@126.com

Bowen Xu[2]*
2 School of Electrical Engineering
Shandong University
Jinan, China
xbw501@163.com

***Abstract*—Electric vehicles (EV) could participate not only in the peak load shifting of power, but also in the frequency regulation of distribution system based on the technology of Vehicle-to-Grid (V2G). Through the transmission of active power between EV's battery and distribution network controlled by bidirectional V2G converter, primary frequency regulation could be achieved locally. In this paper, a two stage V2G converter and relevant control strategy is designed advanced. Then based on the bidirectional V2G converter, primary frequency regulation droop control is introduced to improve previous control strategy. Droop controller designed from EV's droop curve is used to change frequency deviation in distribution into active power deviation, and consequently the value and direction of active power transmitted by V2G converter is adjusted to regulate the frequency. Finally, simulation results verify the feasibility of the droop control for EV and the frequency deviation could be regulated back to acceptable range by V2G converter in distribution feeders.**

Index Terms-- V2G converter; Electric vehicle battery pack; bidirectional active power; primary frequency regulation; droop control

I. INTRODUCTION

The problem of increasing air pollution and fossil fuel exhaustion has attracted great interest on electric vehicle research globally, and traditional internal combustion engine vehicle will be gradually replaced by EV on count of its advantages of clean, efficient and environmental friendly. The battery pack in EV could be used as distributed energy storage unit to realize vehicle-to-grid, which means EV could be charged to absorb surplus power from grid to cover valley times, or be discharged to feed power back to grid during peak load times when it is parking. Based on this technology, the function of EV could be enhanced to fulfill bidirectional active and reactive power control, smart charging/discharging for generation dispatch, renewable energy supporting and balancing, peak load shifting, harmonic filtering, voltage and frequency control and so on[3-4].

The popularization of EV has brought out detailed researches on the V2G technology in recent years. At first, most researches is focused on the circuit topology and control strategy for V2G converter[2], different type of structure and method is proposed to optimize its function. Then further study to improve the performance is carried out by applying new kind of semiconductor devices like SiC[5]. Based on several kinds of common used topology, research interests are attracted on the benefits of active and reactive control[6-7]. The four quarter operation characteristic in P-Q plane allows V2G converter to interact with system and other renewable energy more flexible. Especially the capability of controlling transmitted reactive power enable it to solve the reactive power imbalance and reduce the demand for extra reactive compensation devices[8]-[10]. The realization of V2G power control demonstrates the ability of EV on regulation the system frequency and voltage, as frequency or voltage swing is caused by power flow mismatching between source and load. These researches are developed into two aspects. Some stress on the influence and dispatch of frequency regulation when large-scale EV integrated, modeling the power system and EV response behavior for the optimization of dispatch management at upper layer of power system[11]-[14]. While others focus on the lower layer of power electronic devices, analyzing the suitable control method for V2G device involving regulation[15]-[17]. These detailed devices is the key interface for EV and grid which works similarly with a latest concept called virtual synchronous machine[18], and these researches are the physical foundation of realizing upper layer researches, which is the study point in this paper.

The method of EV regulating primary frequency operated on a specific V2G converter is researched in this paper. The topology and basic control strategy of the two stage converter is reviewed first. Then the frequency regulation droop characteristic curve for EV is analyzed in detail, and droop control strategy and controller for a single converter on the basis of the curve is introduced for the improvement. Finally, simulation on frequency regulation performance of V2G converter unit cooperated controlled voltage source is carried out in PSIM, in which the converter is modeled as power electronic circuit with designed control strategy and frequency regulation droop controller. The analysis and simulations shows that it could control the charging or discharging process, bidirectional active power of EV, and thus compensate for frequency gaps which may be caused by renewable energy source integration in distribution feeders.

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II. TOPOLOGY AND BASIC CONTROL STRATEGY

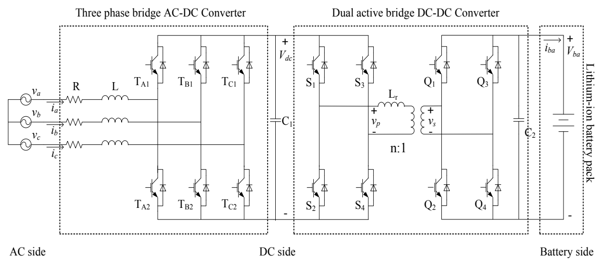


Figure 1. The topology of designed converter

The designed converter is mainly for high power transmission application such as V2G charging piles. A two stage converter consist of voltage source three phase bridge AC-DC converter and dual active bridge DC-DC converter is used for the design, the topology is shown as Fig.1[2]. v_a, v_b, v_c and i_a, i_b, i_c are the three phase voltage and current from AC distribution feeders. V_{dc} is the DC voltage. V_{ba} and I_{ba} is the voltage and current of battery. R is the equivalent resistance of wire and converter. L is the AC input filter inductance. C1 and C2 are the filter capacitances for DC and battery. L_r is the sum of transformer leakage inductance and additional series inductance, and the ratio of high frequency transformer for DAB is n:1. The three-phase bridge AC-DC converter is mainly used for power control of the grid side and four-quadrant power operation, while the DAB DC-DC converter is principally applied to control the charging or discharging of battery side and electrical isolation.

The basic control strategy is designed for AC-DC and DC-DC converter respectively. Double closed-loop control of fixed switching frequency based on direct current feedback is adopted for the AC-DC converter, including feedforward decupling, coordinate transform and PQ calculation. Single phase shift control is employed to the DC-DC converter, the phase shift angle is acquired through active power calculation and current feedback for constant current control. Detailed design and block diagram of basic control strategy is discussed in [2].

The converter topology and control strategy designed above is capable to charge or discharge EV's battery, control bidirectional active or reactive power transmission, operate power in four-quadrant and correct power factor[2].

III. FREQUENCY REGULATION CONTROL STRATEGY

A. *Frequency Regulation Droop Curve*

In power system, traditional frequency regulation is achieved through turbine generator output adjustment. If system frequency shifts with a small scale, the rotate speed of generator unit could be adjusted by prime mover governor and consequently its active power output is adapted for primary frequency regulation. Similarly, each battery pack of EV could be regarded as a power storage and generation unit, the direction and amplitude of its active power could be controlled by V2G converter by means of charging or discharging. So the control strategy is required to simulate the droop characteristic of traditional generator governor. The droop control for distributed generation grid-connected converter could be applied for the V2G converter, following the *f*-*P* droop curve for EV shown as Fig.2.

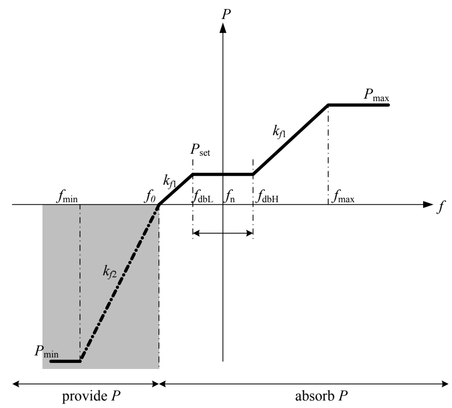


Figure 2. The frequency regulation droop curve for EV.

According to Fig.2, the EV available for frequency regulation service is charged at reference power P_{set} under steady state, where the system frequency is at rated value f_n. The reference charging power could be set by power dispatch department and service provider advanced or owner of EV locally. Even if the EV is not charging (P_{set}=0), it could still participate in primary frequency regulation at any time as long as it is connected to the grid and capable of energy feedback from battery.

If the frequency of distribution feeder deviate from f_n, the V2G converter is supposed to adjust the transmitted power for EV. However, it is to be noted that EV need not to response to every power mismatching, dead band should be considered in other words. Between the upper limit f_{dbH} and lower limit f_{dbL} of the dead band defined, the reference power P_{set} will not be changed in case that persistently charging and discharging power regulation could do harm to the performance and life of EV battery.

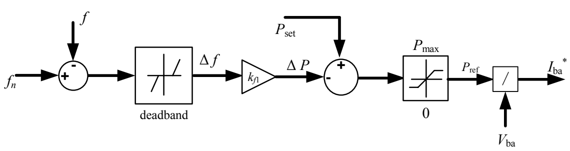
When the frequency deviate over the dead band, the converter will response following the given droop coefficient k_{f1} and k_{f2}. If the frequency deviation is positive (above f_{dbH}), the charging power will be increased and more active power will be absorbed by battery. If the deviation is negative (below f_{dbL}), the charging power will be decreased. If the frequency continue reducing below critical value f_0, the EV will be operated in V2G mode discharging the battery and providing reverse active power, for the reduction of charging load is unable to compensate for power shortage. It also need to be noted that both EV and V2G converter have maximum power limitation and should matched. If frequency deviate too high over $f_{\max}$, EV could be only charged at maximum charging power $P_{\max}$. Similarly if frequency reach the lower point than $f_{\min}$, EV could be discharged at maximum discharging power $P_{\min}$ and reverse power will increase no more.

The droop control above is supposed to be applied in each intelligent electronic interface between EV and grid, which is V2G converter, so that every parked and accessed EV has the potential for primary frequency regulation dispatch. The converter is required to be flexible and adjustable for controlling active power, on account of quick response locally to instant frequency change. What's more, the definition or preset of dead band and droop coefficient should take not only the capacity and characteristic of the distribution system into consideration, but also the performance of EV battery as well as the participation demand of EV owner. The evaluation of the parameter on Fig.2 should go with (1):

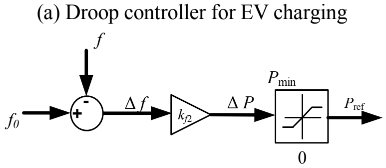
$$\begin{cases} \left|k_{f1}\right| = \dfrac{P_{\max} - P_{\mathrm{set}}}{f_{\max} - f_{\mathrm{dbH}}} = \dfrac{P_{\mathrm{set}}}{f_{\mathrm{dbL}} - f_0} \\ \left|k_{f2}\right| = \dfrac{P_{\min}}{f_0 - f_{\min}} \end{cases} . \tag{1}$$

B. Frequency Regulation Droop Controller

The mentioned droop control strategy should be operated by V2G converter application such as on-board charger or charging pile, so the corresponding droop controller is necessary to be introduced to improve the basic control strategy. The droop controller block diagram is shown as Fig.3. The controller aims to turn the frequency offset into power compensation instruction to set a new reference operating power P_{ref} for V2G converter. So finally the direction and amplitude of active power transmitted by converter is controlled in order that the frequency of connected feeder could be adjusted. The definition of P_{ref} and basic control block diagram is discussed in [2].



(a) Droop controller for EV charging



(b) Droop controller for EV discharging

Figure 3. The frequency regulation droop controller for V2G converter.

If system frequency is higher over f0 ($f > f_0$), the converter is operated with controller block diagram Fig.3(a). EV is in charging state to regulate the active power absorbed, and the controller is supposed to be employed before the current feedback part of the single phase shift control of dual active bridge DC-DC converter[2]. If system frequency is lower than f_0 ($f < f_0$), the converter is operated with Fig.3(b). EV is in discharging state to adjust the power supplied to system, and the controller should be used before the PQ calculation control of the three phase full bridge AC-DC converter[2].

To be specific, in 3(a) the input system frequency f is compared with rated frequency f_{n} and then limited by dead band. If the difference value beyond dead band, then it is output as frequency increment Δf. Notice that the dead band width should be subtract from Δf, that is (2)

$$\Delta f = \begin{cases} (f_{\mathrm{n}} - f) - (f_{\mathrm{n}} - f_{\mathrm{dbH}}) & f > f_{\mathrm{dbH}} \\ (f_{\mathrm{n}} - f) - (f_{\mathrm{n}} - f_{\mathrm{dbL}}) & f_0 < f < f_{\mathrm{dbL}} \\ 0 & f_{\mathrm{dbL}} < f < f_{\mathrm{dbH}} \\ f_0 - f & f < f_0 \end{cases} \tag{2}$$

After then Δf is turned into power increment ΔP by droop coefficient k_{f1} as is a power compensation signal. After subtracted by ΔP, the initial charging power set point P_{set} is adjust to a new active power runtime value. Finally limited from 0 to $P_{\max}$ by a limiter, the controller output a new power command signal P_{ref} for V2G to change charging power. Similarly in 3(b), input f is first turned into increment by critical frequency f_0, then calculated by k_{f2} to be ΔP, and finally new discharging power command signal P_{ref} is acquired after limitation from 0 to $P_{\min}$. According to Fig.2, there is no dead band for controller in 3(b), and the initial value of discharging power is 0. In a word, the P_{ref} is calculated in controller as (3):

$$P_{\mathrm{ref}} = \begin{cases} P_{\mathrm{set}} - k_{f1} \cdot \Delta f & (f > f_0) \\ k_{f2} \cdot \Delta f & (f < f_0) \end{cases} \tag{3}$$

Noticed that $\Delta f < 0$ when $f > f_{\mathrm{n}}$, $\Delta f > 0$ when $f < f_{\mathrm{n}}$ or $f < f_0$. The input system frequency f could be measured by converter locally or given by frequency/power regulation instruction from power dispatch department.

IV. Simulation Analysis

For the application of the model, EV available for primary frequency regulation is supposed to follow some hypothesis[1] below:

1) The state of charge (SOC) of EV battery is assumed to be neither fully charged nor fully discharged, so the SOC could be ignored.

2) The health and life of battery isn't considered. So the continuous frequency regulation will do no harm to battery.

3) The process of battery charging or discharging could last for hours, while the primary frequency regulation could response and accomplish in few second (whether through prime motor or V2G converter). Therefore, the battery characteristics and terminal voltage is supposed to be constant, the power is altered by changing battery current.

Based on such hypothesis, the battery model is simplified as constant DC voltage source in both analysis and simulation. Consequently in Fig.3(a), the current signal I_{ba}* for constant current control of DAB[2] could be computed by using V_{ba} divide new power command signal P_{ref}, and V_{ba} could be measured from battery as constant value.

A. Simulation parameters and conditions

The essence of regulating frequency with V2G technology is compensating system active power peak and valley gaps with the energy stored in EV battery. Usually, the capacity of distribution system (10kV for example) is over several MVA while the maximum capacity of V2G converter or EV battery is at the level of dozens kW, so the ideal way to implement the technology is through charging station (CS). At CS, a large number of EV is managed orderly to charging or discharging hence available capacity is enough for the compensation of power gap from hundreds to thousands kW at tough time. However, the foundation of such CS still is the V2G converter which could control their bidirectional power individually. Therefore the purpose of this paper is to discuss the regulation performance of each converter. So the simulation is carried in PSIM based on some simplified conditions.

TABLE I. SIMULATION PARAMETERS

AC-DC converter	
RMS of phase voltage v_a, v_b, v_c/V	220
Voltage of DC side V_{dc}/V	700
Phase inductance of AC side L/mH	4
Phase equivalent resistance of AC side R/Ω	0.1
Capacitance of DC side C_1/μF	3300
Switching frequency f_s/Hz	10000
DC/DC converter	
The sum of series inductance and transformer leaking inductance L_r/μH	80
Ratio of transformer n	70/36
Capacitance of battery side C_2/μF	2200
Voltage of battery side V_{ba}/V	360
Switching frequency f_s/Hz	20000
Droop parameters	
Charging rate point P_{set}/W	7200
Maximum charging power P_{max}/W	3000
Maximum discharging power P_{min}/W	3000
Nominal frequency f_n/Hz	50
Upper limit of dead band f_{dbH}/Hz	50.2
Lower limit of dead band f_{dbL}/Hz	49.8
Critical frequency f_0/Hz	49
Droop coefficient for charging k_{f1}/W/Hz	9000
Droop coefficient for discharging k_{f2}/W/Hz	10000

Instead on the level of multi-node distribution system, the simulation focuses on the frequency regulation performance of a single V2G converter with detailed topology and control strategy designed. The distribution feeder to which the converter connected is simplified as controlled voltage source whose frequency is controlled by active power transmitted on AC bus. And the source capacity is matched with the maximum capacity of the converter so that the single converter with EV battery is enough for power compensation and frequency regulation. The simulation parameters is shown as Table Ⅰ. The frequency corresponding to maximum charging/discharging power is f_{max} and f_{min}, which ought to be constant calculated from parameters rather than preset value for controller.

B. Simulation results

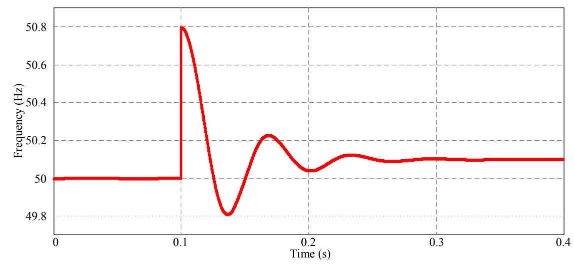


Figure 4. The source frequency regulation curve when $f > f_n$

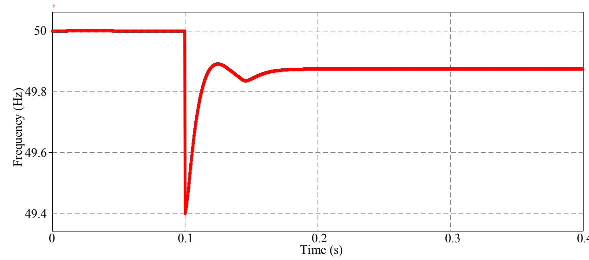


Figure 5. The source frequency regulation curve when $f_0 < f < f_n$

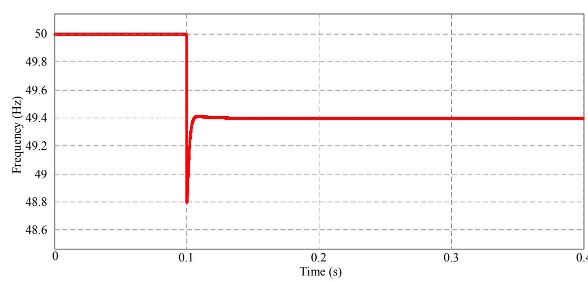


Figure 6. The source frequency regulation curve when $f < f_0$

If f rises over f_n, the frequency regulation curve is shown as Fig.4. At 0.1s, the frequency steps up to 50.8Hz, the converter is required to control EV to absorb surplus active power from source. According to equation (2), the Δf is -0.6Hz, and the charging power is increased from 7.2kW to 12.6kW. As a result, f start to decrease and return to tolerance range. After transient adjustment it finally stabilize at 50.1Hz at about 0.3s.

If f falls under f_n but not too much beneath f_0, the frequency regulation curve is shown as Fig.5. At 0.1s, the frequency sags to 49.4Hz, the converter should reduce EV charging power to lower the load for source. The Δf is worked out to be 0.4Hz, so the charging power decreased from 7.2kW to 3.6kW. It is shown that f rises back to about 49.9Hz after 0.2s and remain stable on acceptable level.

If f falls sharply below f_0, the frequency regulation curve is shown as Fig.6. The frequency drop down to 48.8Hz at 0.1s, indicating that there is a large active power deficiency in source. So the reduction of charging load is not enough to fill the valley, the EV should discharging at V2G mode. As the Δf is 0.2Hz, EV is operated to discharge at 2kW to compensate for source by V2G converter. Then f recover quickly to some extent and finally stabilize at 49.4Hz. If f is supposed to return to the level closer to 50Hz, the k_{f2} should be set bigger so that the V2G converter could response more sensitively to frequency deviation and EV could be discharged at higher power. Besides, the regulation process in Fig.6 is more quickly than in Fig.4 and 5 because there is no dead band in the controller of discharging.

V. CONCLUSIONS

Based on a bidirectional V2G converter and control strategy designed previously, the method of EV participating in primary frequency regulation is discussed in this paper. First the frequency regulation droop characteristic curve for EV is analyzed in detail. Then the droop control strategy and controller on the basis of the curve is introduced to evolve the V2G converter. Theoretical analysis shows that the improved V2G converter connected with EV battery is capable of regulating the frequency of distribution system feeders by controlling the charging or discharging active power. Finally, simulation in PSIM verifies that the V2G converter and frequency regulation droop control strategy is able to control the bidirectional active power and charging or discharging process of EV, thus compensate for frequency gaps in distribution feeders.

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