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Comprehensive DC Power Balance Management in High-Power Three-Level DC–DC Converter for Electric Vehicle Fast Charging

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***Abstract*: -- With the increasing popularity of electric vehicles, there is an urgent demand to shorten the charging time, so the development of high-power charging stations with fast chargers is necessary to alleviate range anxiety for drivers. The charging station based on the neutral-point-clamped (NPC) converter can bring many merits, but it has unbalanced power problems in the bipolar dc bus. To solve this issue, comprehensive dc power balance management (PBM) in conjunction with high-power three-level dc-dc converter based fast charger is proposed in this paper. The active dc power balance management (APBM) is proposed to assist the central NPC converter in balancing power so that the additional balancing circuit is eliminated; while the passive dc power balance management (PPBM) is proposed to eliminate the fluctuating neutral-point currents and to ensure the balanced operation of fast chargers. The principles of APBM and PPBM are researched, the efficient integration between them is studied, and the overall control scheme for the fast charger is proposed. The power balance limits of APBM are explored, while the circulating currents of PPBM are analyzed. Simulation and experimental results are presented to verify the effectiveness of the proposed fast charger with PBM functions.**

***Keywords* — Dc power balance management, electric vehicles, fast charger, plug-in hybrid electric vehicles, three-level dc–dc converter.**

I. INTRODUCTION

As viable alternatives to conventional internal combustion engine vehicles (ICEVs), the plug-in hybrid electric vehicles and electric vehicles (EVs) are increasing their market share gradually because of decreased fossil fuels consumption and reduced greenhouse gas emission. Surveys show that the range per charge, the charging time, the available charging facilities are the greatest concerns of consumers, which are also the main factors influencing their purchase of EVs. In order to allow the future widespread use of EVs, there is an urgent demand to develop fast chargers to shorten the charging time, and to deploy the high-power charging stations infrastructure to alleviate range anxiety for drivers. If fast chargers reduce the EVs replenishing time within acceptable levels comparable to the usual refueling of ICEVs, and the high-power charging stations spread all over the cities and highways as the gas stations do, the acceptance of EVs will be enhanced. The high-power charging station architectures include two main groups: One uses common ac bus, the other uses common dc bus, but the latter seems a preferable one as less conversion stages are needed so that higher system efficiency can be obtained, and it is easier to integrate the storage systems (batteries or ultra-capacitors) and the renewable energy sources (the photovoltaic and wind). The common dc-bus architecture can be realized as uni polar dc bus using two- level voltage source converters or bipolar dc bus

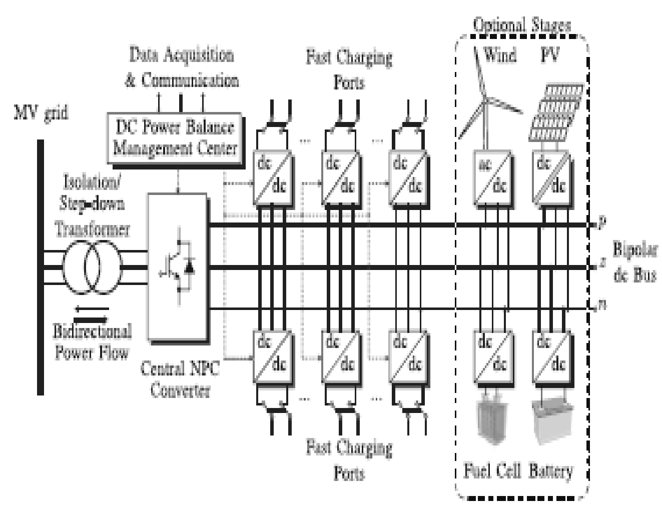

Fig. 1. Bipolar dc bus charging station architecture

using three-level neutral point-clamped (NPC) converters. The bipolar dc bus architecture has been previously analyzed in using an NPC converter as the central grid-tied ac–dc

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converter. The bipolar dc architecture as shown in Fig. 1 offers more power capacity, more flexible ways for the loads to be connected to the dc bus. Moreover, the line-to-line voltage waveform of the two-level voltage source converter contains three voltage levels, whereas the NPC converter produces five voltage levels and the equivalent switching frequency of the NPC converter is twice the device switching frequency, leading to lower dv/dt, lower filtering requirement, and better current performance. However, the configuration in suffers from imbalanced power between the positive dc bus and the negative dc bus, because each dc bus is independent and their loads differ most of the time. The imbalanced power can lead to worse grid-side currents and make the bipolar dc bus unbalanced, even outside of the controllable zone. In order to solve this problem, the study in introduced an additional balancing circuit, but with the drawbacks of additional cost and poorer efficiency.

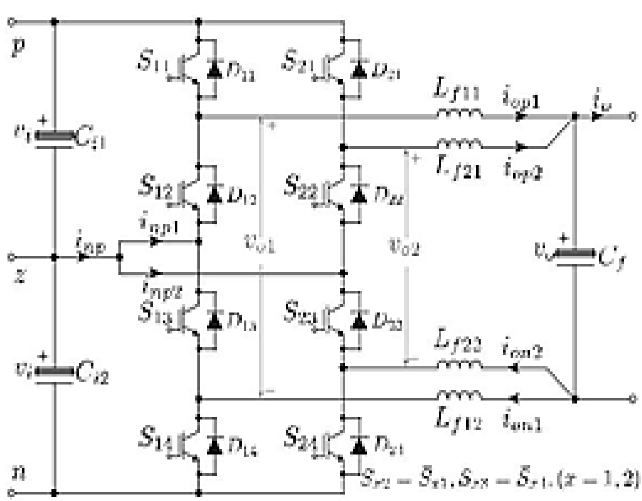

Fig. 2. Proposed three-level dc–dc converter topology.

This paper proposes comprehensive dc power balance management in conjunction with high-power three-level dc–dc converter based fast chargers for high-power charging stations with a bipolar dc bus. The proposed fast charger with dc power balance management capability eliminates the need for additional balancing circuits and high-frequency transformers, thereby improves the overall system efficiency. Meanwhile, since the dc power balance management task is partly achieved by the three-level dc–dc converters, the central NPC converter has more freedom to accurately control the grid-side currents leading to higher power quality. To solve the unbalanced dc power problem among the positive dc bus and the negative dc bus, the comprehensive dc power balance management is proposed. The active and passive dc power balance managements (APBM and PPBM) are investigated from the aspects of operating principles, balance limits and circulating currents. The efficient integration between APBM and PPBM is studied, and the overall control scheme for the fast charger is proposed. The performance of the proposed fast charger and control algorithms are verified through simulation and experimental results.

II. HIGH-POWER THREE-LEVEL DC–DC CONVERTER

A. Topology Description

The structure of the proposed converter for high-power fast chargers is presented in Fig. 2. It consists of two parallel three level dc–dc converter units to handle the high charging current, and the input terminals *p, z, n* directly fit the bipolar dc bus of the central charging station shown in Fig. 1. Each unit is composed of four switching devices along with four freewheeling diodes, and two output inductors. The nomenclature of each component is shown in Fig. 2. The converter structure is modular in nature because the parallel dc–dc converters share common input filter capacitors C_{i1} , C_{i2} , and common output filter capacitor C_f , so the power capacity can be easily scaled up by connecting more number of dc–dc converters in parallel.

B. Modulation and Operating Principle

The modulation method and operating principle of the proposed fast charger is presented in Fig. 3, for the case when the system is under balanced power conditions and the two converter units operate in the in-phase mode (with their gating signals having no phase difference). Under this mode, the instantaneous power sharing of the proposed dc–dc converter is always equal, which is different from the interleaved converters. Two operating regions are presented to analyze the converter. Fig. 3(a) shows the converter waveforms when $d_{x1}=d_{x4}=d \leq 0.5$, and Fig. 3(b) shows the waveforms when $d_{x1}=d_{x4}=d > 0.5$. The modulation signals d_{x1} and d_{x4} are duty cycles generated by the controller, where *x* denotes 1 or 2 corresponding to unit 1 or unit 2. As shown in Fig. 3, the modulation signals (duty cycle values) d_{x1} and d_{x4} are compared with two 180◦ interleaved carrier signals c_1 , c_4 to generate the gate signals for outer switches S_{x1} and S_{x4} , while the inner switches S_{x2} and S_{x3} operate complementarily to their corresponding adjacent outer switches, respectively. This leads to four operating stages: 14, 13, 23 and 24, where the numbers denote which switches are turned ON. The output voltage of stage 14 is the total dc side voltage $2v_i$; the stage 23 produces zero output voltage; while the stages 13 and 24 generate the same output voltage v_i but have opposite neutral-point currents, which enables the converter to have the dc power balance management capability.

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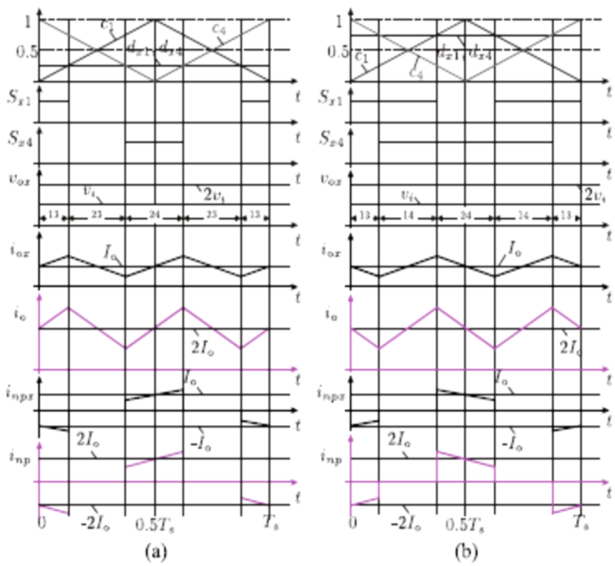

Fig. 3. Modulation and operating principle. (a) d ≤ 0.5. (b) d > 0.5.

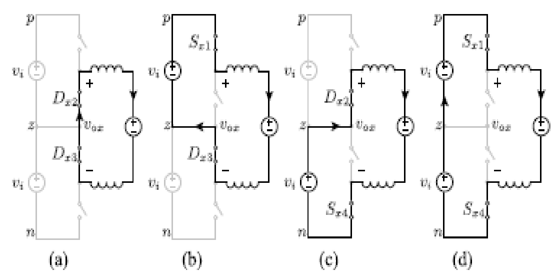

Fig. 4. Four operating stages and their equivalent circuits. (a) 23. (b) 13. (c) 24. (d) 14.

III. ACTIVE DC POWER BALANCE MANAGEMENT (APBM)

APBM Principle

Because there are inherent balance limits of the central NPC converter (refer to Fig. 1) , in order to assist it in balancing power between the dc buses and remove the additional balancing circuit, APBM for fast chargers is proposed. Under the APBM mode, the fast chargers can perform the power balance task actively so that the central NPC converter has more freedom to control the grid-side currents, resulting in better power quality.

To simplify the analysis, it is assumed that the split dc-link capacitor voltages are balanced and equal to *vi* , the output current polarity is positive (G2V operation), and the output filter capacitor along with the battery load is replaced by an ideal voltage source, then the equivalent circuits of the four operating stages (23, 13, 24, 14) are shown in Fig. 4. It can be seen that operating stages 23 and 14 do not have impact on power balance, as there is no current flowing through the neutral point *z*, while switching stages 13 and 24 have the opposite impact on the power balance: Stage 13 draws power from the positive dc bus while stage 24 draws power from the negative dc bus. Therefore, based on this feature, the APBM principle can be formulated: For a charging station, if the power on the positive dc side *Pp* is lower than the power on the negative dc side *Pn* , it is necessary to make the dwell time for state 13 longer while the time for state 24 has to be shorter, so that the fast charger draws more power from the positive bus to aid the charging station to balance power. On the contrary, if *Pp* is larger than *Pn* the opposite regulation needs to be done, that is, time for stage 13 should be reduced while time for stage 24 should be increased. Fig. 5 shows the APBM principle explicitly only considering *d* > 0.5 and the positive output current, however is also valid for *d* ≤ 0.5. Under balanced power conditions, the modulation indexes *dx*1 and *dx*4 are both equal to *d*, but under the presence of unbalances they must be regulated to different values accordingly. Compared to the balanced scenario (shown by black line) where *dx*1 = *dx*4 = *d* and the average value of *i*npx is zero, when *Pp* < *Pn* , the dwell time for stage 24 is decreased while time for stage 13 is increased as shown in the shaded area o Fig. 5(a), leading to *dx*1 > *dx*4 (shown by blue line) and the negative average value of *i*npx. However, the average value of output voltage *vox* remains unchanged. The opposite situation is shown in Fig. 5(b), where *Pp* > *Pn* as the dwell time for stage 24 is increased while time for stage 13 is decreased, resulting in *dx*1 < *dx*4 and the positive average value of *i*npx. Aforementioned analysis is based on the assumption that the output current is positive, but when the output current is negative (V2G operation), the regulation process should be done inversely.

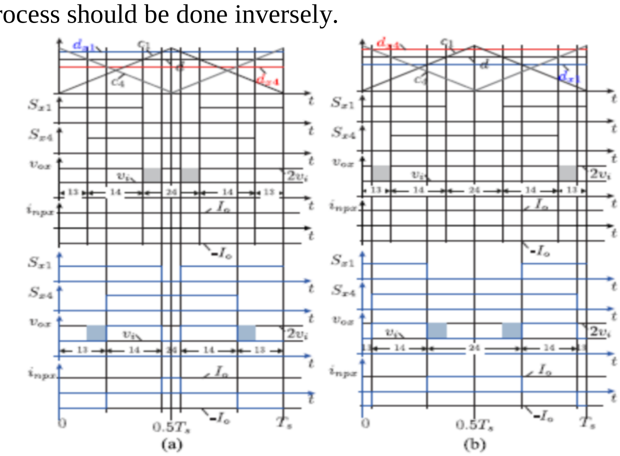

Fig. 5. APBM principle. (a) dx1 > dx4 . (b) dx1 < dx4 .

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IV. PASSIVE DC POWER BALANCE MANAGEMENT (PPBM)

PPBM Principle

Since the entire three-level dc–dc converter based fast chargers have access to the neutral point of the central NPC converter as shown in Fig. 6.1, although the average capacitor voltages are equal under balanced operating conditions, the accumulated total neutral-point current fluctuation is drastic and leads to big voltage fluctuations at the dc-side capacitors, which is harmful to the safety and lifetime of capacitors. In order to solve this problem, the PPBM is proposed. Under the PPBM mode, the proposed parallel three-level dc–dc converters feature a virtual disconnection to the neutral-point, working as the two-level converter connected to the total dc bus directly, hence minimizes the presence of the total neutral-point current and guarantees the balanced power operation of fast chargers. From the charging station point of view, if all the fast chargers are operating under the PPBM mode, there will be no unbalanced power between the dc buses, however, as the total neutral-point current is zero, it cannot balance the dc power actively, that is the reason why it is called PPBM.

As demonstrated earlier in Fig. 6, the two stages 13 and 24 produce the same output voltage magnitude but with opposite neutral-point current polarities, while states 14 and 23 do not influence the neutral-point currents. Hence, if the two dc–dc converter units operate in the out-of-phase mode (with their gating signals having 180◦ phase difference) as shown in Fig. 6, the neutral-point currents *inp*1 , *inp*2 will cancel each other, ideally leading to the total neutral-point current *inp* = 0 while the output voltage remains unaltered. From the charging station point of view, the dc–dc converter operates like a virtual two-level converter because it fetches power from the total dc bus directly. Obviously, this operation is beneficial to the charging station with a bipolar dc bus, because the fast charger does not cause power imbalance problems. When under the PPBM mode, from the gating signals point of view, the proposed operating mode is similar with the operating mode of two interleaved converters, because both of them have 180◦ phase difference between the gating signals. But the proposed two parallel converters receive power from different dc sides, which is still different from the power sharing of two interleaved converters. Comparing the total neutral-point current *inp* shown in Fig. 6 with the one shown in Fig. 6, it can be found there are no fluctuant neutral-point currents under the PPBM mode. Because of this, issues related with both power and voltage fluctuations are minimized, as the presence of many fast chargers and operating simultaneously do not have a strong impact on the dc bus, leading to reduced requirements for the dc-side capacitors.

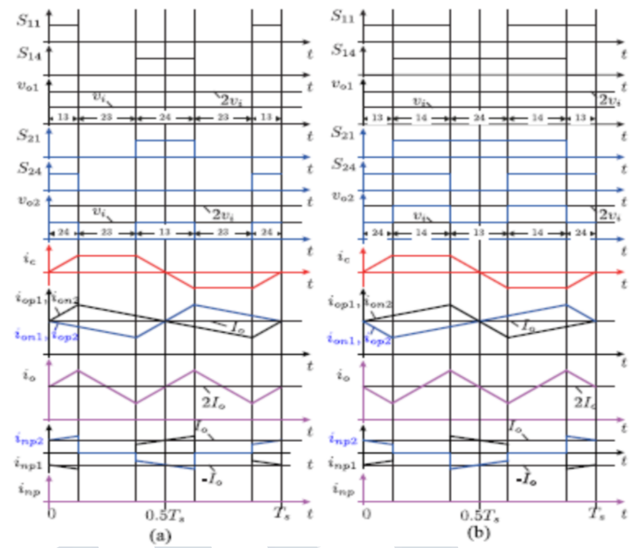

Fig. 6. PPBM principle. (a) d ≤ 0.5. (b) d > 0.5.

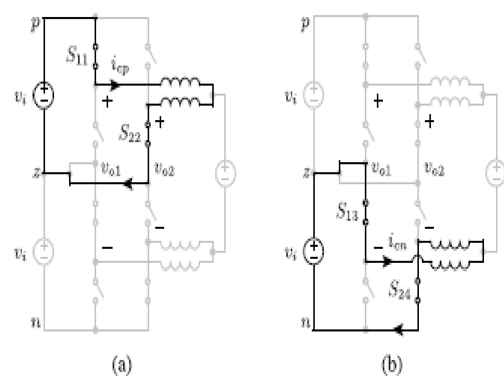

Fig. 7. Paths for the circulating currents: (a) upper circulating current icp , (b) lower circulating current icn .

V. COMPREHENSIVE DC POWER BALANCE MANAGEMENT

Based on the proposed APBM and PPBM as discussed in the previous two sections, the comprehensive dc power balance management is formulated. When the imbalanced power between the dc buses is outside of the predefined controllable zone of the central NPC converter, the APBM is activated to assist it in balancing power so that additional balancing circuits can be eliminated; while when the imbalanced power is within its balanced zone, the PPBM is chosen to ensure the balanced operation of fast chargers and minimize the fluctuant neutral point currents. By this way, the comprehensive dc power balance management combines the advantages of APBM and PPBM

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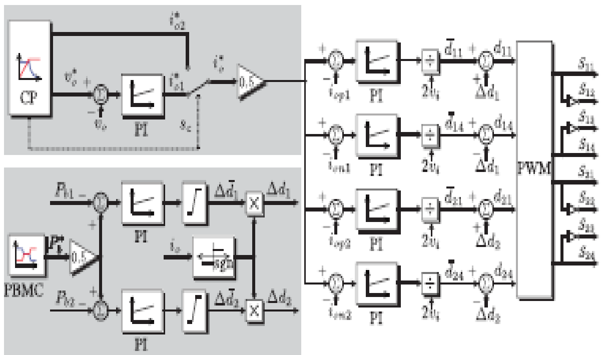


Fig. 8. Control diagram for the fast charger with comprehensive dc power balance management.

TABLE I
SIMULATION AND EXPERIMENTAL PARAMETERS

Parameter	Sym.	Sim. value	Exp. value
Total dc voltage	$2v_i$	$3.\bar{3}$ p.u.	$3.\bar{3}$ p.u.
Input capacitance	C_i	0.56 p.u.	0.56 p.u.
Output inductance	L_f	1.25 p.u.	1.25 p.u.
Output capacitance	C_f	$0.\bar{6}$ p.u.	$0.\bar{6}$ p.u.
Switching frequency	f_s	72 p.u.	72 p.u.
Base frequency	f_B	60 Hz	60 Hz
Base voltage	V_B	600 V	42 V
Base power	P_B	240 kW	1.2 kW

Note: Output side values are used as the base quantities.

to achieve most beneficial cooperation for the overall power balance of the charging station. Therefore, the transition between APBM and PPBM is proposed to be triggered by the power difference Δ*P* between *Pp* and *Pn*. When Δ*P* is outside of a predetermined region, the APBM is selected; when it falls into this region, the PPBM is chosen. The explicit transition rule for it is as follows:

$$\text{PBM} = \begin{cases} \text{APBM}, & \text{when } \Delta P \notin [-P_{b\epsilon}, P_{b\epsilon}] \\ \text{PPBM}, & \text{when } \Delta P \in [-P_{b\epsilon}, P_{b\epsilon}] \end{cases} \quad (9)$$

Where *Pb* is chosen based on the balance limits of the central NPC converter and the balance task sharing between it and the operating fast chargers. Then, the control scheme for the fast charger with comprehensive dc power balance management is presented in Fig. 8. The upper grey box represents the output voltage and current control, where the charging profile (CP) provides the reference current *io*2 , the reference voltage *v*o* , and the switch signal *sc* to control the transition between the constant current (CC) charging mode and the constant voltage (CV) charging mode. Then, as the two units share the total output current, the current reference of each unit is set to *io/*2 and the four output currents of two converter units are controlled using four PIs, then the outputs of PIs are divided by the total input voltage 2*vi* to generate the original modulation signals ¯ *dx*1, ¯ *dx*4. The lower grey box shows the comprehensive dc power balance management, where the power balance management center (PBMC) commands the required balance power reference *P*b* , which is easy for PBMC to calculate after collecting voltages and currents information

From all loads connected to the bipolar dc bus of a charging station, and knowing the number of operating fast chargers *n*

$$P_b^* = \Delta P/n = (P_n - P_p)/n. \quad (10)$$

Meanwhile, the balance power *Pbx* generated by each converter unit can be obtained based on the Figs. 4 and 5

$$P_{bx} = (d_{x1} - d_{x4})v_i i_{ox}. \quad (11)$$

The balance power is controlled with two PIs, generating the control signalsΔ¯ *dx, which* are limited to be within the boundary [−Δˆ *dx, Δ*ˆ *dx*], and Δˆ *dx* is defined as follows:

$$\Delta\hat{d}_x = \begin{cases} \min\{\bar{d}_{x1}, \bar{d}_{x4}\}, & \bar{d}_{x1,x4} \le 0.5 \\ 1 - \max\{\bar{d}_{x1}, \bar{d}_{x4}\}, & \bar{d}_{x1,x4} > 0.5. \end{cases} \quad (12)$$

Then, depending on the power flow direction, the power balance control signal Δ*dx* is finally obtained by multiplying Δ¯ *dx* by the sign of the total output current *io*

$$\Delta d_x = \Delta\bar{d}_x \text{sgn}(i_o). \quad (13)$$

After obtaining Δ*dx* , and using the original modulation signals ¯ *dx*1 , ¯ *dx*4 , the final modulation signals *dx*1 , *dx*4 are calculated
According to the following equations:

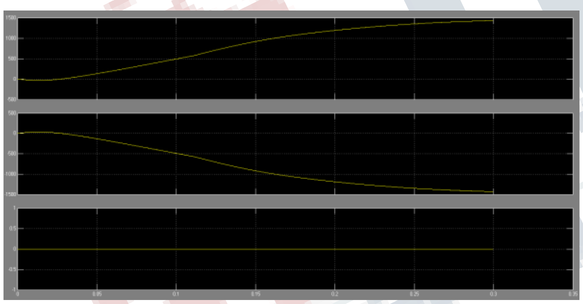
$$d_{x1} = \bar{d}_{x1} + \Delta d_x \quad (14)$$

$$d_{x4} = \bar{d}_{x4} - \Delta d_x. \quad (15)$$

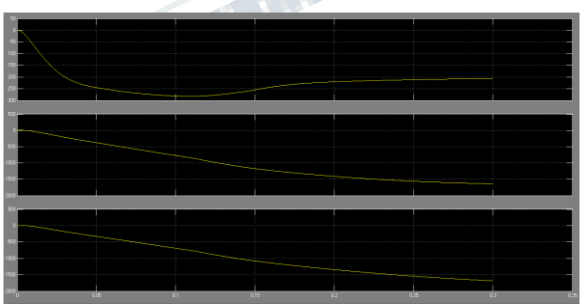
Then the gating signals are generated through the modulation discussed in Section II-B. It should be noticed that when PPBM is chosen, the switching signals for the two units should be phase shifted 180◦.

VI. SIMULATION RESULTS

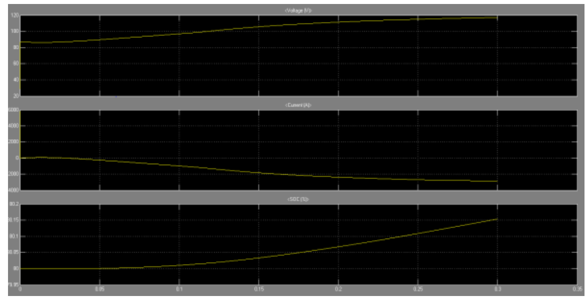
The proposed fast charger with comprehensive dc power balance management is simulated using MATLAB/Simulink. A 240-kW converter is designed for the validation, and the detailed system parameters are shown in Table I. To validate the scheme, the following scenario is simulated. The converter begins operating under CC charging mode, and four scenarios are forced in order to illustrate the dc power balance management with $d \leq 0.5$. The converter begins operating in APBM with $P*b = -1$p.u., then in order to emphasize the features of PPBM, no PBM is performed after 0.030 s (under balanced power conditions). Then PPBM is activated at 0.034 s and then the converter is set to operate in APBM with $P*b =$ 1p.u. Then when the system triggers the control scheme to operate under CV charging mode, the same test is performed once again now with $d > 0.5$. Then, the dc power balance management under CC mode is validated through Fig. 9, where the total output current reference $i*o$ is set to 1 p.u. throughout the test, while $P*b$ is changed in order to validate all the operation modes as presented in Fig. 9. From Fig. 9, it can be seen that the total output current io is controlled to its reference $i*o$ tightly, meanwhile the balance power Pb is regulated to track its reference $P*b$ very well, which also validates the maximum balance power is the output power when $d < 0.5$. Moreover, it becomes clear that, under PPBM, the total neutral-point current inp is zero, hence decreasing the power and voltage fluctuations at the dc-side, compared with its value when no PBM is used under balanced power conditions.



(a)



(b)



(c)

Fig. 9. MATLAB simulation results

Similar to the CC mode, in the CV mode, the current balance between the two units is also reached well, as shown in Fig. 9. Moreover, PPBM can also eliminate the fluctuant neutral-point currents and keep total current ripple unchanged at the expense of a little increase in the current ripple of each unit; while APBM leads to increased ripples both on the unit output current and on the total output current. The presented results verify the principle and performance of the proposed converter with comprehensive dc power balance management, which are consistent with the theoretical analysis in the previous sections.

VII. CONCLUSION

The high-power three-level dc–dc converter based fast charger with comprehensive dc power balance management is proposed for high-power charging stations with a bipolar dc bus. The proposed fast charger has the dc power balance capability and enables the elimination of additional balancing circuits and high-frequency transformers, thereby improves the overall system efficiency. It gives the central NPC converter more freedom to control grid-side currents, so enhances the power quality. Meanwhile, the use of parallel three-level dc–dc converters brings lower current stress and lower output current ripples, and the power capacity can be easily scaled up due to its modularity. Both the active and passive dc power balance managements (APBM and PPBM) are proposed. Their operating principles and the efficient cooperation between them are studied. The idea of PBMC is introduced for the charging station, and the overall control diagram for fast chargers is developed. The APBM is proposed to assist the central NPC converter in balancing power when the imbalanced power is out of its predetermined controllable zone; while the PPBM is proposed to ensure the balanced operation of fast chargers themselves and eliminate the drastic fluctuant neutral-point currents so as to decrease the dc-side capacitors requirement. The power balance limits of APBM are explored for the PBMC to allocate the power

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balance tasks among the operating fast chargers and the central NPC converter. Meanwhile, the circulating currents of PPBM are also analyzed. Through the simulation and experimental results, it has been demonstrated that the proposed fast charger performs very well in achieving the comprehensive dc power balance management in addition to the basic function of EV fast charging.

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