Review of Current Quality Compensators for High Power Unidirectional Electric Vehicle Battery Charger

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***Abstract*—This paper reviews and compares different possible current quality compensating solutions for a high power unidirectional electric vehicle (EV) battery charger with three-phase power supply. Their pros, cons and characteristics for the high power EV battery charger are also summarized. Simulation results of different compensating solutions for a 50kW EV charging system are also provided to illustrate and compare their compensating performances and characteristics.**

I. INTRODUCTION

To reduce fuel usage and greenhouse emissions, electric vehicle (EV) application is growing more interest in nowadays [1]. Thus, battery chargers play an important role in the development of EV. For low power EV charger (Level 1 and 2 [1]), which is more common in nowadays, it works with a single-phase power supply, and the current quality compensation is usually done by a boost converter for power factor correction (PFC). And this kind of low power EV charger typically includes a single-phase front-end PFC followed by an isolated dc-dc converter [1]–[3]. For high power EV charger (Level 3 [1]), the research studies are not much among this existing literatures. Therefore, this paper focuses on the Level 3 fast and high power EV chargers with three-phase power supply.

For a high power unidirectional EV battery charger, it is typically composed of three main circuits: a three-phase input ac-dc conversion circuit, a current quality compensation circuit and an isolated dc-dc conversion circuit. Due to low initial cost and simple control consideration, the ac-dc conversion circuit is usually done by an uncontrollable diode rectifier bridge rather than a fully controllable ac-dc converter. However, this rectifier circuit will cause significant current distortion and low power factor at the three-phase system input side. To eliminate those current quality problems, this paper aims to review and compare different possible current quality compensating topologies for the high power EV battery charger. And their compensating performances in a 50kW EV charging system are investigated and compared by using power system computer aided design / electromagnetic transient in dc system (PSCAD/EMTDC) simulation tool.

II. HIGH POWE UNDIRECTIONAL ELECTRIC VEHICLE BATTERY CHARGER WITHOUT CURRENT QUALITY COMPENSATION

The circuit configuration of a high power unidirectional battery charger without current quality compensation is shown in Fig. 1, where the subscript '*x*' denotes phase *a*,*b*,*c*. v_{sx} and i_{sx} are the system voltage and current, L_s is the system input inductance, i_{EVCx} is the phase current flows to the EV charger, V_{in}, i_{in} and C_{in} are the dc input voltage, current and capacitor, V_{out}, i_{out} and C_{out} are the dc output voltage, current and capacitor. The current quality compensation for the high power unidirectional battery charger in Fig. 1 can be done by either series or shunt compensation. The series compensators will be connected after the three-phase full diode bridge rectifier, while the shunt compensators will be connected in front of that. Once the dc input voltage V_{in} can fall within its designed range, the designed dc output voltage V_{out} level for the EV can be achieved by control the duty ratio of the traditional phase-shift resonant dc-dc converter. To simplify the following current quality compensation analysis and verification, those parts after the dc input current capacitor will be modeled as a variable resistor $\boldsymbol{R}$. In next section, the different series and shunt current quality compensators will be discussed in details, and their corresponding control block will be given.

III. DIFFERENT CURRENT QUALITY CCOMPENSATING SOLUTIONS FOR THE HIGH POWER UNIDIRECTIONAL ELECTRIC VEHICLE BATTERY CHARGER

The different possible current quality compensating circuits for the high power unidirectional EV battery charger

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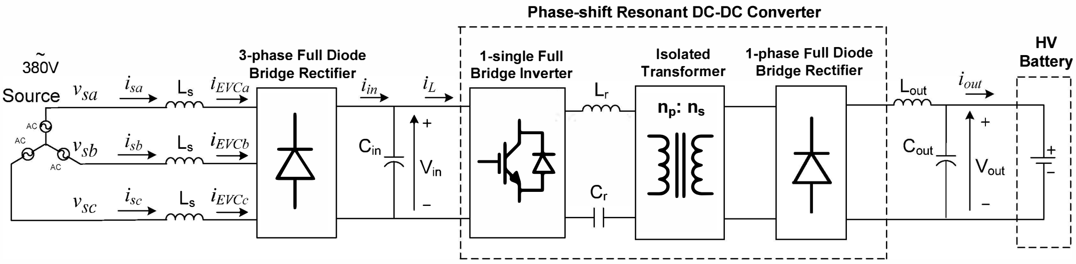


Figure 1. A high power unidirectional battery charger without current quality compensation.

are shown in Figs. 2 – 5 respectively. Figs. 2 and 3 show two series type current quality compensation, while Figs. 4 and 5 show the shunt type compensation. For the series current quality compensators such as: conventional single switch power factor correction (PFC) [4]–[6] and three-phase three-level power factor correction (TPTL-PFC) [7] as shown in Figs. 2 and 3, their corresponding control algorithms and system parameters can be designed accordingly in [4]–[7]. Triangular carrier-based sinusoidal PWM method can be applied to generate the PWM trigger signals for the switching devices, in order to obtain approximately sinusoidal system input current. For the shunt current quality compensators such as: active power filter (APF) [8],[9] and LC coupling hybrid active power filter (LC-HAPF) [10]–[13] as shown in Figs. 4 and 5, their reference reactive, harmonic and dc-link voltage control compensating currents are determined by the three-phase instantaneous *pq* theory [14]. Both the hysteresis PWM and triangular carrier-based sinusoidal PWM method can be applied to generate the PWM trigger signals for the switching devices, in order to inject the compensating current into the system for current quality compensation. Thus, an approximately sinusoidal system input current can then be achieved.

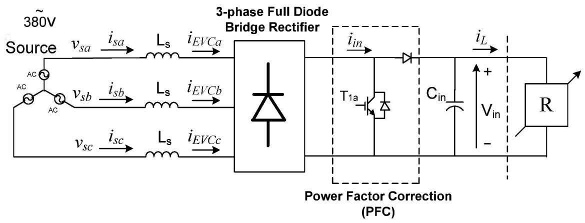


Figure 2. EV charger with a single switch PFC (boost rectifier) cuurent quality compensation [4]-[6].

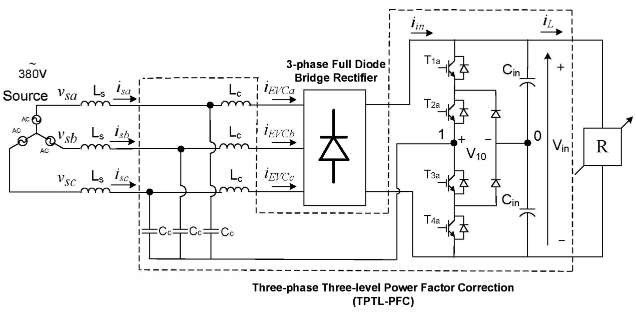


Figure 3. EV charger with TPTL-PFC current quality compensation [7].

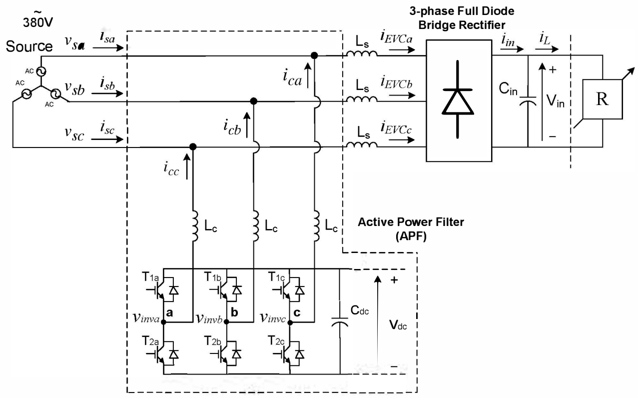


Figure 4. EV charger with APF current quality compensation [8]-[9].

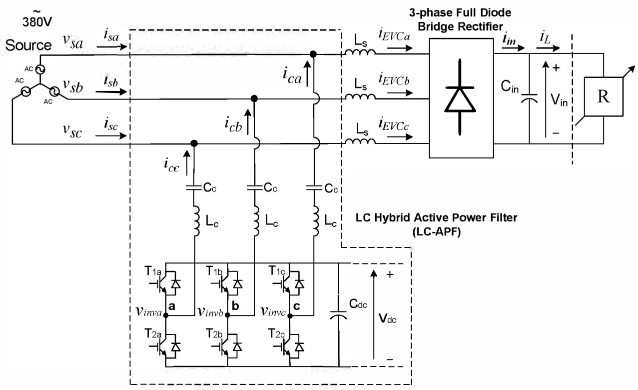


Figure 5. EV charger with LC-HAPF current quality compensation [10]-[13].

And the control block diagrams of the single switch PFC, TPTL-PFC, APF and LC-HAPF for current quality compensation in a high power EV charger are illustrated in Fig. 6.

For the control block diagram of the single switch PFC as shown in Fig. 6(a), the detected dc input voltage V_{in} is initially compared with its reference V_{in}^*, then their difference is passing through a proportional or proportional and integral (P/PI) controller. After that, the P/PI controller output is compared with a fixed frequency triangular wave carrier T_{ri}, in order to generate trigger signals for the switching device as shown in Fig. 2.

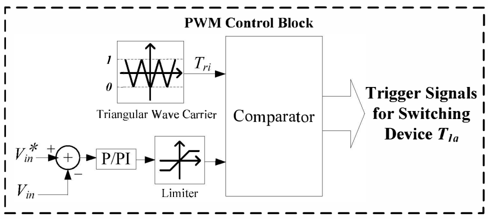
For the control block diagram of the TPTL-PFC as shown in Fig. 6(b), a fixed duty ratio (D) value of 0.5 is compared with a fixed frequency triangular wave carrier T_{ri}, in order to generate trigger signals for the switching device as shown in Fig. 3.

For the control block diagram of the APF as shown in Fig. 6(c), the APF reference reactive and harmonic compensating currents (i_{cx_q}, the subscript $x=a, b, c$ for three phases) are determined by using the three-phase instantaneous pq theory [14]. Moreover, the dc-link voltage control compensating currents (i_{cx_dc}) are also determined by the three-phase instantaneous pq theory. Then the final reference compensating current i_{cx}^{*} can be obtained by summing up the i_{cx_q} and i_{cx_dc}. After that, the final reference and actual compensating currents i_{cx}^{*} and i_{cx} will be sent to the current PWM control part in order to generate trigger signals for the switching device as shown in Fig. 4. Both the hysteresis PWM and triangular carrier-based sinusoidal PWM method can be applied to the PWM control part.

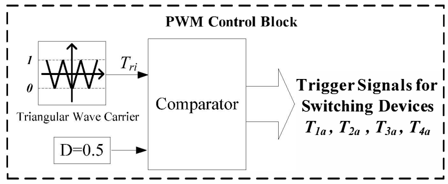
For the control block diagram of the LC-HAPF as shown in Fig. 6(d), it has the same instantaneous power compensation control block and final reference compensating current and PWM control block, the only difference is the dc-link voltage control block. Besides the dc-link voltage control error signal feedback as active P_{dc} component, this error signal is also feedback as reactive Q_{dc} component. And this dc-link voltage control scheme is explained in details in [13]. Similar as APF, the final reference and actual compensating currents i_{cx}^{*} and i_{cx} will be sent to the current PWM control part in order to generate trigger signals for the switching device as shown in Fig. 5. Moreover, both the hysteresis PWM and triangular carrier-based sinusoidal PWM method can be applied to the PWM control part.

IV. SIMULATION VERIFICATION

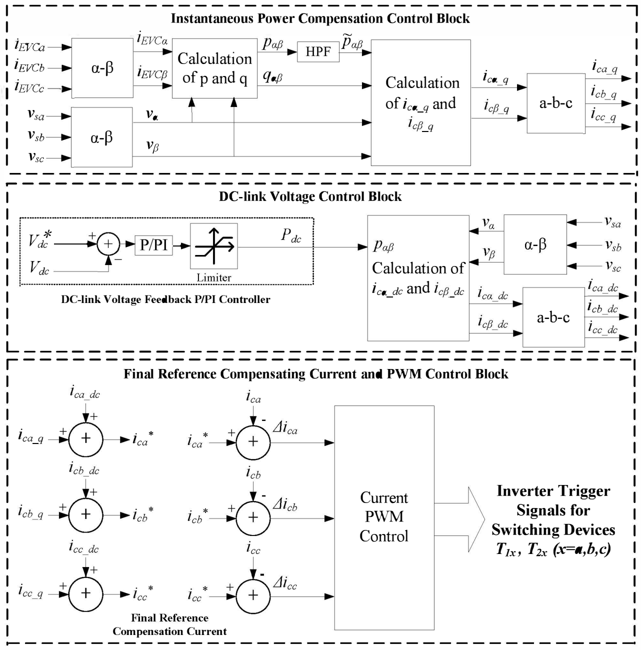
Simulation studies were carried out by using PSCAD/EMTDC. The dc input voltage is set to V_{in}=500V ~ 540V, V_{sx} =380V, L_s =0.9mH, C_{in} =2500µF. The full loading (V_{in}=500V, R=5Ω) of the EV charger will be 50kW. And the current quality compensating solutions are operating at a switching frequency of 5kHz. In the following, the simulated system voltage v_{sa} and current i_{sa} waveforms and power quality (PQ) data before and after the conventional PFC, TPTL-PFC, APF and LC-HAPF compensation for full and half EV charging loadings are illustrated in Fig. 7 and summarized in Table I – V.



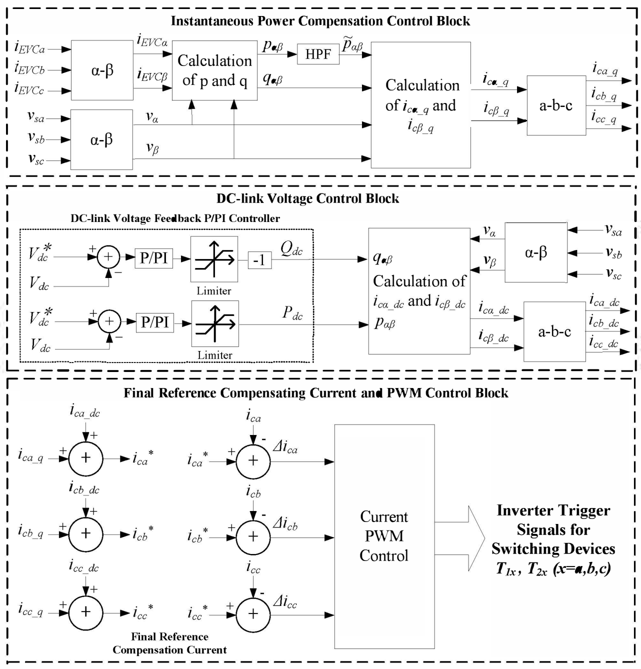
(a)



(b)



(c)



(d)

Figure 6. Control block diagram for: (a) conventional PFC, (b) TPTL-PFC, (c) APF and (d) LC-HAPF compensation.

A. *After Conventional Power Factor Correction (PFC) Compensation*

From Fig. 2, by applying an insufficient dc input voltage level V_{in}= ~540V to the conventional PFC, compared Fig. 7(a) with Fig. 7(b) and Table I with Table II, the conventional PFC cannot perform satisfactory reactive power (Q_{sxf} = 3180.7var, 7360.3var) and current harmonics (THD_{isx} >20%) compensation for the EV charger during both half and full loading situations, in which the compensated THD_{isx} does not satisfy the international standards (THD_{isx} <16% for IEC and THD_{isx} <20%) [15] – [16]. And the system current i_{sx} increases after compensation. To improve the PFC performances, the required V_{in} will be very high [4] – [6], which is not appreciated for the downstream parts of the EV charger.

B. *After Three-phase Three-Level Power Factor Correction (TPTL-PFC) Compensation*

From Fig. 3 and Ref. [7], when the capacitor C_c and inductor L_c are designed based on full load and V_{in} =500V consideration, C_c =4.4μF and L_c=53μH. The duty ratios of two sets of switching devices are chosen as a fixed D=0.5. Compared Fig. 7(a) with Fig. 7(c) and Table I with Table III, even though the TPTL-PFC is designed based on V_{in}=500V and full load situation, it can perform reactive power (displacement power factor, DPF≥0.99) and current harmonics (THD_{isx} <11%) of the EV charger during both half and full load situations, in which the compensated THD_{isx} satisfies the international standards [15] – [16]. However, during half loading, it yields a higher V_{in} =543V, unless the duty ratio D is being changed. This action results in deteriorating the compensating performances. Moreover, the system current i_{sx} increases after compensation.

C. *After Active Power Filter (APF) Compensation*

From Fig. 4, the coupling L_c = 3mH, dc-link capacitor C_{dc} = 5mF and dc-link operating voltage V_{dc} = 800V. Compared Fig. 7(a) with Fig. 7(d) and Table I with Table IV, with a high dc-link voltage level 800V, the APF can significantly compensate reactive power (DPF=1) and current harmonics (THD_{isx} <8%) of the EV charger during half and full loading situations, in which the compensated THD_{isx} satisfies the international standards [15] – [16]. Actually, its operation range can be from no load to full load.

D. *After LC-coupling Hybrid Active Power Filter (LC-HAPF) Compensation*

From Fig. 5, the coupling C_c =200μH and L_c = 2mH (tuned at 5th order), dc-link capacitor C_{dc} = 5mF and dc-link operating voltage V_{dc} = 280V. Compared Fig. 7(a) with Fig. 7(e) and Table I with Table V, with a medium dc-link voltage level 280V, the LC-HAPF can significantly compensate reactive power (DPF=1) and current harmonics (THD_{isx} <6%) of the EV charger during half and full loading situations, in which the compensated THD_{isx} satisfies the international standards [15] – [16]. Moreover, the system current i_{sx} can be reduced after compensation. And it can obtain the best reactive power and current harmonics compensation among the four current quality compensators. However, its operation range can be from half load to full load only with V_{dc}=280V.

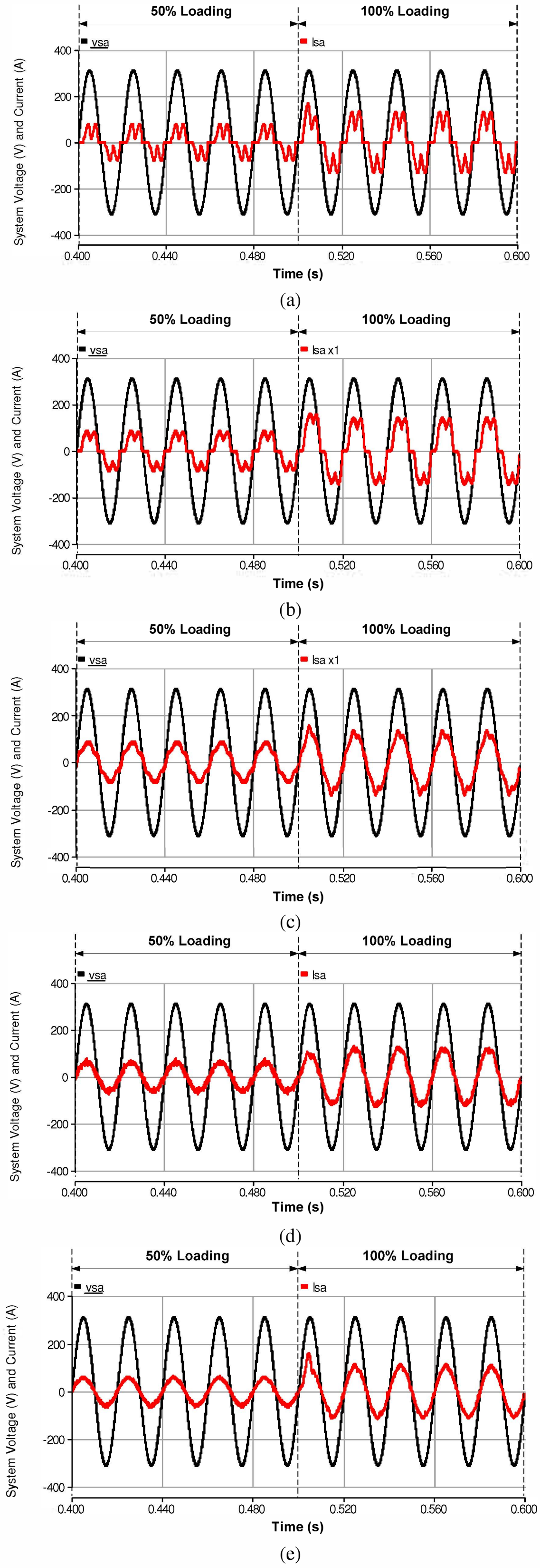


Figure 7. System voltage v_{sx} and current i_{sx} of EV charger wihtout and with different current quality compensators: (a) before compensation, (b) conventional PFC, (c) TPTL-PFC, (d) APF and (e) LC-HAPF.

TABLE I. SIMULATION RESULTS OF EV CHARGER BEFORE COMPENSATION

	Before Compensation					
Different Cases:	Q_{sxf} (var)	DPF	i_{sx} (A_{rms})	THD_{isx} (%)	P_{sxf} (W)	V_{in} (V)
50% loading (R=10Ω)	2053.5	0.972	44.5	51.3	8539.6	510.0
100% loading (R=5Ω)	4432.6	0.966	83.1	36.9	16588.8	502.0

TABLE II. SIMULATION RESULTS AFTER CONVENTIONAL PFC COMPENSATION

	After Conventional PFC Compensation (V_{in}=540V)					
Different Cases:	Q_{sxf} (var)	DPF	i_{sx} (A_{rms})	THD_{isx} (%)	P_{sxf} (W)	V_{in} (V)
50% loading (R=10Ω)	3180.7	0.960	55.1	29.1	10980.6	543.0
100% loading (R=5Ω)	7360.3	0.935	96.5	22.8	19523.3	530.0

TABLE III. SIMULATION RESULTS AFTER TPTL-PFC COMPENSATION

	After TPTL-PFC Compensation (Design based on full Loading)					
Different Cases:	Q_{sxf} (var)	DPF	i_{sx} (A_{rms})	THD_{isx} (%)	P_{sxf} (W)	V_{in} (V)
50% loading (R=10Ω)	1276.9	0.995	56.9	10.4	12262.3	543.0
100% loading (R=5Ω)	2829.7	0.990	87.4	8.5	18788.5	500.0

TABLE IV. SIMULATION RESULTS AFTER APF COMPENSATION

	After APF Compensation (V_{dc}=800V)						
Different Cases:	Q_{sxf} (var)	DPF	i_{sx} (A_{rms})	THD_{isx} (%)	P_{sxf} (W)	V_{in} (V)	i_{cx} (A_{rms})
50% loading (R=10Ω)	125.2	1.000	44.8	7.5	9495.8	502.0	23.4
100% loading (R=5Ω)	110.4	1.000	82.4	6.6	18259.7	504.0	35.5

TABLE V. SIMULATION RESULTS AFTER LC-HAPF COMPENSATION

	After LC-HAPF Compensation (V_{dc}=280V)						
Different Cases:	Q_{sxf} (var)	DPF	i_{sx} (A_{rms})	THD_{isx} (%)	P_{sxf} (W)	V_{in} (V)	i_{cx} (A_{rms})
50% loading (R=10Ω)	-182.7	1.000	41.0	5.2	8951.4	501.0	22.8
100% loading (R=5Ω)	233.6	1.000	73.7	3.9	16118.9	502.0	34.2

The comparison between different current quality compensating solutions for the 50kW unidirectional high power EV battery charger are summarized in Table VI.

V. CONCLUSIONS

In this paper, the different possible current quality compensating circuits for the high power unidirectional battery charger are reviewed and compared, in which:

1) Conventional PFC is not an appropriate compensating solution for the EV charger because it requires a very high dc input voltage V_{in} to compensate the current quality problems, which would strongly affect the rating design of the downstream parts of the EV charger.
2) The control of the TPTL-PFC is simple. However, its dc input voltage V_{in} level will be varied under different % loading situation, unless the duty ratio is being changed. But this action will deteriorate the compensating performances. The reactive power compensation capability is fair, and it requires high operating current for IGBT and diode, thus increasing power loss in high power situation
3) APF requires relatively lower operating current than TPTL-PFC and its compensation range can cover from 0% - 100% loading. However, it requires a high dc-link operating voltage, thus high voltage rating requirements of IGBT and diode are essential. To further reduce the compensated THD_{isx} < 5%, extra high pass or/and LC filters are required. Moreover, the control of APF is not simple.
4) LC-HAPF requires much lower dc-link operating voltage than APF and lower operating current than TPTL-PFC. Moreover, it can obtain the best reactive power and current harmonics compensation. However, it requires the largest number of components, and its compensation range mainly depends on the dc-link voltage level. Moreover, the control of LC-HAPF is not simple.

After taking consideration of the current quality compensating performances, control complexity and initial cost, APF and LC-HAPF can be applied to the high power unidirectional EV battery charger for current quality compensation.

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TABLE VI. COMPARISON BETWEEN DIFFERENT CURRENT QUALITY COMPENSATION SOLUTIONS FOR 50KW UNIDIRECTIONAL HIHG POWER EV CHARGER

	Conventional PFC (V_{in}=540V)	TPTL-PFC (V_{in}=543V <50%>, V_{in}=500V <100%>)	APF (V_{in}=500V, V_{dc}=800V)	LC-HAPF (V_{in}=500V, V_{dc}=280V)
No. of IGBT	1 (1200V, 250A)	4 (600V, 200A)	6 (1600V, 80A)	6 (600V, 80A)
No. of Diode	2 (1200V, 250A)	6 (600V, 200A)	6 (1600V, 80A)	6 (600V, 80A)
No. of AC Inductor	---	3 (53μH, 200A)	3 (3mH, 80A)	3 (2mH, 80A)
No. of AC Capacitor	---	3 (4.4μF, 400V)	---	3 (200μF, 400V)
No. of DC Capacitor	---	2 (2500μF, 400V)	1 (5mF, 1200V) Practical: Series connection of 3 (10mF, 400V)	1 (5mF, 400V)
Voltage Signal Sensor Circuit	1	1	4	4
Current Signal Sensor Circuit	---	---	6	6
Initial Cost	Lowest	Low	High	Medium
Reactive Power Comp.	No for low V_{in}	Fair	Very Good	Very Good
Current Harmonics	THD > 20%	THD < 11%	THD < 8%	THD <6%
Compensation Range	50% - 100% Load	50% - 100% Load	0% - 100% Load	50% - 100% Load
Fault Protection	Easily bypass by a controllable 1-phase switch	Easily bypass by two controllable 1-phase switches	Easily bypass by a controllable 3-phase switch	Easily bypass by a controllable 3-phase switch
Control Algorithm	Simple	Simple	Not simple	Not simple