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Analysis and Modelling of Power-Dependent Harmonic Characteristics of Modern PE Devices in LV Networks

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Abstract—This paper presents results of experimental and analytical evaluation of power-dependent harmonic emission of three common types of modern low voltage (LV) power electronic (PE) devices. After a detailed analysis of comprehensive test results, based on both existing and new waveform distortion indices, the development of component-based models of PE devices is discussed. The paper demonstrates the importance of including PE devices’ controls for accurate modelling of their characteristics over the entire range of operating powers. Most of the analysed PE devices exhibit strong power-dependent changes of characteristics, additionally influenced by supply voltage conditions, which are important for the analysis of both existing networks and future “smart grids”.

Index Terms—Harmonic analysis, modelling, power quality, power electronics, smart grid, testing, waveform distortion.

I. INTRODUCTION

An increasing number of modern low voltage (LV) power electronic (PE) devices utilize high-frequency switching circuits and complex controls for improved performance, better reactive power regulation and increased efficiency. Common examples of power-consuming PE devices are switch-mode power supplies (SMPS’s) and electric vehicle battery chargers (EVBCs) with active power factor control (a-PFC) circuits. In the case of power-generating LV PE devices, the most common technology is photovoltaic inverters (PVIs) with pulse-width modulated (PWM) control.

The harmonic emissions of PE equipment are governed by well-established international standards, e.g. [1-3] in the EU, [4] in the US and [5] in Australia and New Zealand. Most of the relevant standards, however, specify that harmonic emission tests of LV PE devices shall be conducted under sinusoidal voltage supply conditions with equipment operating at the rated power, \( P_{\text{rated}} \), or at maximum total harmonic current in amps [1]. Identical test conditions are specified for EVBCs, with [6-7] citing [1-2] for harmonic compliance.

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The experimental and analytical frameworks are presented in Section II and illustrated on measured data in Section III. Section IV describes the model development process. Section V provides conclusions and areas of further work.
II. EXPERIMENTAL AND ANALYTICAL FRAMEWORKS

A. Current Waveform Distortion Indices Used for Analysis

1) Existing harmonic distortion indices: Current harmonic distortion of PE devices can be presented in absolute values, denoted as total harmonic current THI, (1), or in relative values, either as total harmonic distortion of current \( THD_i \), (2), or as the total demand distortion \( TDD \), (3). As \( THC \) and \( THDI \) are related by a constant factor \( (100/I_{\text{fund}}) \) and have similar meaning, only \( THC \) and \( THDI \) are considered for further analysis in this paper.

\[
THC = \frac{\sqrt{\sum_{h=2}^{N} (I_h)^2}}{I_{\text{fund}}} \times 100 \quad (1)
\]

\[
THDI = \frac{1}{I_{\text{fund}}} \sqrt{\sum_{h=2}^{N} (I_h)^2} \times 100 = \frac{THC}{I_{\text{fund}}} \times 100 \quad (2)
\]

\[
TDD = \frac{1}{I_{\text{fund}}} \sqrt{\sum_{h=2}^{N} (I_h)^2} \times 100 = \frac{THC}{I_{\text{fund}}} \times 100 \quad (3)
\]

where: \( I_{\text{fund}} \), \( I_h \), and \( I_a \) are the r.m.s. values of the rated current, the fundamental component and the current harmonic of order \( h \), respectively. The maximum considered harmonic order \( H \) is typically 40 or 50, representing LF harmonics.

\( THC \) and \( THDI \) indices allow to perform harmonic emission analysis from two different perspectives. \( THC \) allows analyses of the impact of emissions on voltage harmonic levels in the network (i.e. network perspective) for studying, e.g. electromagnetic compatibility or evaluating the contribution of PE devices to the total harmonic distortion. \( THDI \) assesses the harmonic performance of an individual PE device (i.e. equipment perspective), indicating how the device’s harmonic currents change in relation to the fundamental current, which is important for equipment manufacturers and end-users.

In this paper, the power-dependent changes in harmonic emissions are assessed by calculating \( I_{\text{fund}}(P) \) and \( I_h(P) \), and then \( THC(P) \) and \( THDI(P) \) at a given operating power \( P \).

2) Existing waveform distortion indices: Expressions (1)-(3) typically assess only harmonic emissions and do not take into account other types of waveform distortion, which might be present in modern PE devices, e.g. sub-harmonics, inter-harmonics and higher frequency emissions [9]. For evaluating the total current waveform distortion, [10] defines the fundamental factor, FF, and the total distortion content, TDC (4)-(5). In this paper, these are also considered as functions of the device operating power.

\[
FF(P) = \frac{I_{\text{fund}}(P)}{I_{\text{tot}}(P)} \quad (4)
\]

\[
TDC(P) = \frac{I_{\text{non-fund}}(P)}{I_{\text{tot}}(P)} = \frac{\left[ I_{\text{harm}}(P) + I_{\text{PF}}(P) + I_{\text{non-LF}}(P) \right]}{I_{\text{tot}}(P)} = \sqrt{1 - FF^2(P)} \quad (5)
\]

where: \( I_{\text{fund}}(P) \), \( I_{\text{harm}}(P) \) and \( I_{\text{non-fund}}(P) \) are the r.m.s. values of the total current, fundamental current and non-fundamental current, respectively, at given operating power \( P \).

3) Two new waveform distortion indices: To allow for a more detailed analysis, this paper introduces two new indices: the total harmonic factor, restricted to LF harmonics, \( THFLF \) (6), and the total non-(LF)-harmonic distortion factor, \( TNHDF \) (7). These indices accompany the previously introduced \( TDC \) and \( FF \) indices and extend their application.

The value of two new indices lies is in their ability to make a further distinction between the contributions of the LF harmonics and all other distortions. As shown later in the paper, this is of particular importance for the analysis of modern PE devices, for which LF harmonics might not be the most significant part of the total waveform distortion.

\[
THFLF(P) = \frac{\left[ I_{\text{harm}}(P) + I_{\text{PF}}(P) + I_{\text{non-LF}}(P) \right]}{I_{\text{fund}}(P)} \quad (6)
\]

\[
TNHDF(P) = \frac{I_{\text{non-harm}}(P)}{I_{\text{fund}}(P)} = \frac{\left[ I_{\text{harm}}(P) + I_{\text{PF}}(P) + I_{\text{NF}}(P) \right]}{I_{\text{fund}}(P)} = \sqrt{(1 - FF^2(P)) \cdot (TDC(P)/100)^2} \quad (7)
\]

where \( I_{\text{non-harm}}(P) \) is the r.m.s. values of non-LF-harmonic (non-fundamental) distortion current at given operating power \( P \).

B. Test Set-Up and Test Parameters

A fully automated test-bed, with accuracies better than 5%, 2% and 1% for individual harmonic magnitudes higher than 50mA, 100mA and 200mA, respectively, is used for all tests [8]. It consisted of a 1MS/s acquisition system and a controllable three-phase power source with programmable voltage waveforms and source impedance values, allowing configuration of specific waveform-impedance combinations. The testing is controlled from a centralized workstation with respect to two test parameters:

1) The source impedance value: was set to either a) the minimum possible source impedance, \( ZS1=0 \) (due to the impedance of a cable connecting the PE device to the power source and the power source itself) or b) the maximum expected LV network source impedance \( ZS2 \), consisting of \( Z_{\text{phase}}=(0.24 + j0.15) \Omega \) and \( Z_{\text{source}}=(0.16 + j0.10) \Omega \) [13].

2) The ac supply voltage waveform: was emulated as an ideally sinusoidal reference waveform (WF1) and as two distorted voltage waveforms (WF2 and WF3). The two distorted waveforms are derived from the measurements in LV networks and have different harmonic magnitudes and phase angles (further information is available in [14]). The “flat-top” WF2 is typical of a network supplying a large number of residential customers with 2-pulse rectifiers, while the “pointed-top” WF3 is typical for LV networks with a large number of industrial customers with 6-pulse rectifiers [15].

The two distorted waveforms used for testing include phase angle variations, which are known to influence the operation of PE control circuits. Further information on the impact of phase angle dependencies and cross-coupling of harmonics on the emission of PVIs and EVBCs can be found e.g. in [16-18].
III. MEASUREMENT RESULTS

A. PV Inverters (PVIs)

The three measured PVIs include both single-phase and three-phase types, featuring transformerless, LF and HF transformer topologies. Figs. 1a and 1b show that the THC values for two out of the three PVIs do not reduce at lower power outputs, while the corresponding THD values suggest that their harmonic emissions might be of concern. For example, THC(P) values of PVI-1 for WF1 and ZS1 start to increase in low power mode, resulting in THC values higher than 75% of Prated and almost equal to values at Prated. All three PVIs have very low THD values at high operating powers for WF1 and ZS1. In very low power mode, however, their THD(P) values increase up to 100 times. These changes would not be identified if the tests were performed with the operating powers set at 50% [3] or 25% [5] of Prated.

The presence of supply voltage distortion and source impedance might have a very strong impact. THC(P) values of PVI-2 for WF2-3 and ZS2 increase several times with respect to the THC(P) values for WF1 and ZS1 (note a six-fold THC increase in Fig. 1b and logarithmic scale in Fig. 1a). Similarly, THC(P) values of PVI-1 for WF2-3 and ZS2 are 50% higher than THC(P) for WF1 and ZS1, with THC at 20% of Prated almost equal to THC at 75% of Prated. Moreover, in very low power mode, THD(P) values of PVI-2 for WF2 and ZS2 are almost 600% and the device will disconnect from the supply, indicating that PVI-2 cannot control its harmonic emission in very low power mode when connected to grids with typical background distortion and source impedance values.

The THC(P) and TNHDF(P) indices introduced in this paper provide further insights into the sources of the harmonic distortion. The contribution of the fundamental current of all tested PVIs to their total operating current starts to decrease around 25% of Prated (most notably for PVI-2, Fig. 1c). In very low power mode, the non-fundamental currents of all PVIs are several times higher than their fundamental currents. For example, Fig. 1d shows that a significant part of current waveform distortion of PVI-3 is not due to LF harmonics. These results clearly indicate that if only LF-harmonic-related indices (THD, THC and/or TDD) are used for the analysis, this might not result in a full assessment of the current waveform distortions of modern PE devices.

B. Switch-Mode Power Supplies (SMPS’)

Test results for two SMPS’ with a-PFC circuits (standard desktop PC supplies) at different powers are shown in Fig. 2. In very low power operating mode, SMPS-2 enters unstable operating conditions, which prevented further testing. To analyze the whole range of operating powers, a component-based SMPS model is developed in the next section and used to complement the available test results. Fig. 2a shows noticeable changes in the harmonic performance of the two tested SMPS’ in low power mode. The results for SMPS-1 show that its harmonic currents in the very low power mode are almost equal to its fundamental currents (THD of 80-100%), although the THC values of both SMPS’ in Fig. 2b exhibit continuous reduction with decreasing operating power.

The impact of supply voltage distortions is less pronounced than for PVIs, with SMPS-2 displaying negligible change. For SMPS-1, with reference to WF1 (sinusoidal), THD decreases for the “flat-top” WF2 and increases for the “pointed-top” WF3, while THC reduces for both WF2 and WF3. Fig. 2c shows that the contribution of the fundamental current to the total current of SMPS-1 starts to decrease in low power mode, becoming equal to the contribution of the non-fundamental current in very low power mode, as indicated by the THD(P) values in Fig. 2a. Fig. 2d presents the contributions from the LF harmonics and other current waveform distortion to the total current, confirming that LF harmonics (THF(LF)) have the largest contribution to the waveform distortion, as non-LF-harmonic distortion (TNHDF) remains very small for all considered WFs and ZS values.
C. EV Battery Chargers (EVBCs)

The three EVs, which are available in the EU market, were subject to tests in which their on-board single-phase Level-2 chargers were measured during the standard charging cycle. Based on the state-of-charge of the EV battery, the EVBCs first operated at rated power (constant-current, CC, mode) and then transferred to constant-voltage (CV) mode, characterized by the reduced power demands. In CV mode, the control disconnected the EVBCs at low operating powers (indicated in Fig. 3a), preventing analysis for the entire operating range (see the EVBC model developed in Section IV for further results).

Fig. 3a shows that the \( THD \) values of all EVBCs start to increase in low power mode. Some high \( THD \) values are measured in “stand-by” mode, i.e. when charging is finished but the EVBC is still connected to the supply. However, this is not considered further due to the negligible power demands. Similar to the SMPS’, there is very little effect of supply voltage distortion and source impedance.

The \( THC \) plots in Fig. 3b indicate that the absolute harmonic currents of two EVBCs steadily decrease with reduced powers. For EVBC-3, however, after an initial reduction there is a slight increase below 40% of \( P_{\text{rated}} \). Fig. 3c shows that the contribution of the fundamental current of the tested EVBCs is somewhat reduced in (very) low power mode, with limited contribution of non-fundamental currents. In other words, the measured EVBCs have much better control of current waveform distortion than the PVIs and SMPS’. The available \( THF_{LF} \) in Fig. 3d confirm that LF harmonics are the main contributor to the total waveform distortion, as the \( TNHDF \) values are very low.
IV. MODELLING OF MODERN PE DEVICES

Building on the previous work of the authors (e.g. [14-15]), this section presents the development of component-based SMPS, EVBC and PVI models, capable of accurately reproducing their current waveform distortion characteristics over the entire range of operating powers and for different supply conditions. The models are derived in a general form, in order to represent generic PE devices that are currently available on the EU domestic market, but model parameters have been adjusted to match the tested PE devices and to validate simulation results with the measurement results. All model parameters are included in the appendix.

A. Modelling of SMPS’

Fig. 4 shows the developed component-based SMPS model, consisting of an input EMI filter, standard diode bridge rectifier (DBR) and dc-dc boost converter with a-PFC circuit. The modelled EMI filter is a balanced “T” filter, which, together with the a-PFC circuit, controls EMI and harmonic emission in accordance with prescribed limits e.g. [1]. After the DBR, there is a small input capacitor for stabilizing the input voltage in accordance with the peak current requirement of the SMPS [19]. The boost converter and the a-PFC circuit determine the power-dependent changes in the current waveform distortion characteristics of the modelled SMPS, since they directly regulate both the input dc voltage and input inductor current (and, therefore, the input ac current).

Fig. 5 details the a-PFC circuit developed as an important part of the SMPS model. It uses average current mode control, consisting of an inner current loop and an outer voltage loop. For the outer voltage loop, the sensed output voltage, is scaled in time domain for SMPS-2 at two different power levels. The difference, i.e. the voltage error, is supplied to the voltage controller, whose output is multiplied with the haversine function, which is scaled down from the input voltage to produce the inductor current reference waveform. The scaled inductor current is compared with its reference waveform, with the difference fed to the current controller. Finally, the output of the current controller is compared with a high-frequency sawtooth signal to generate the PWM control signal for the boost converter switch. Additional information on the developed SMPS model and its parameters are given in [15] and in Table A.1 in the appendix.

![Fig. 4. The schematic of the developed component-based SMPS model.](image)

![Fig. 5. The block diagram of a-PFC circuit applied to the SMPS model.](image)

B. SMPS Model Validation and Discussion

To validate the developed SMPS model, the model parameters were set to emulate the characteristics of SMPS-2 from Section III.B. Good matching between the measured and simulated input ac current waveforms for different operating powers and supply conditions in Fig. 6 suggests that the developed model is capable of correctly reproducing the current waveform distortion characteristics of the real device.

Transfer of the a-PFC control from continuous conduction mode (CCM) to discontinuous conduction mode (DCM) is the main reason for increased waveform distortion of the input ac current at low and very low operating powers, Figs. 6a-6c. During the DCM operation, the inductor current is often zero during the switching cycle, as the a-PFC controller is unable to follow its reference waveform. If the a-PFC circuit is not properly integrated with the SMPS model, it would be very difficult to obtain good matching between the simulation and measurements results. Fig. 6d provides an example (only for illustrative purposes), comparing the results for the developed SMPS model with and without the a-PFC circuit (in the EU market, SMPS with P_{rated}<75W may not include a-PFC [1]).

![Fig. 6. Comparison of measurement (“meas”) and simulation (“sim”) results in time domain for SMPS-2 at two different power levels.](image)
a) THD(P) and THC(P)

b) FF(P) and TDC(P)

c) THFg(P) and TNHFDF(P)

Fig. 7. Comparison of measured (“meas”, hollow symbols) and simulated (“sim”, solid symbols) waveform distortion indices of SMPS-2.

Fig. 8. The schematic of the developed component-based EVBC model.

Fig. 9. The block diagram of a-PFC control applied to the EVBC model.

D. EVBC Model Validation and Discussion

The developed EVBC model (with parameters adjusted to EVBC-1 from Section III.C) is again validated by comparing measured and simulated input ac current waveforms, Fig. 10. Again, good matching between the results in the time-domain is obtained for all supply and operating conditions.

Although there is a higher distortion and ripple content in the instantaneous ac current in low power mode, its waveform is much better regulated by the modelled EVBC’s a-PFC circuit, than in the case of SMPS (see also Section IV.G). It can be concluded that the a-PFC (i.e. type, circuit topology, control strategy and control settings) will determine harmonic emission and waveform distortion characteristics. In the case of the EVBC, the a-PFC basically controls input ac current waveform to emulate the input ac voltage waveform.
model can be found in [20] and in Table A.1 in the appendix.

Grid current control consists of an inner current loop (in stationary reference frame, SRF, and a PR controller) and an outer voltage loop (with the reference for the grid current magnitude realised by a PI controller). At the output, a scale factor multiplies the averaged three-phase reference voltage waveform to the inverter model. More details of the SRF-PLL control waveforms at the full bridge inverter terminals, which are fed to the inverter model.

The grid synchronization part detects the instantaneous ac supply voltage waveform and applies an abc to dq transform as input into a PLL for determining the synchronous reference frame into the closed loop control. The grid current control consists of an inner current loop (in abc stationary reference frame, SRF, and a PR controller) and an outer voltage loop (with the reference for the grid current magnitude realised by a PI controller). At the output, a scale factor multiplies the averaged three-phase reference voltage waveforms at the full bridge inverter terminals, which are fed to the inverter model. More details of the SRF-PLL control model can be found in [20] and in Table A.1 in the appendix.

The developed component-based PVI model is illustrated in Fig. 12. It consists of a PV panel (represented by a controlled current source), dc-side capacitor, full bridge inverter and its control circuit and output filter. The control of the full bridge inverter is shown in Fig. 13 and can be divided into two parts. The grid synchronization part detects the instantaneous ac supply voltage waveform and applies an abc to dq transform as input into a PLL for determining the synchronous reference frame into the closed loop control. The grid current control consists of an inner current loop (in stationary reference frame, SRF, and a PR controller) and an outer voltage loop (with the reference for the grid current magnitude realised by a PI controller). At the output, a scale factor multiplies the averaged three-phase reference voltage waveforms at the full bridge inverter terminals, which are fed to the inverter model. More details of the SRF-PLL control model can be found in [20] and in Table A.1 in the appendix.

The developed PVI model (with parameters adjusted to PVI-2 from Section III.A) is again validated by comparing measured and simulated ac current waveforms, Fig. 14. As for the two previously considered types of modern PE devices, the presented results indicate that the developed component-based PVI model is capable of correctly representing the power-dependent harmonic and waveform distortion characteristics for different operating and supply conditions.

### F. PVI Model Validation and Discussion

The developed PVI model (with parameters adjusted to PVI-2 from Section III.A) is again validated by comparing measured and simulated ac current waveforms, Fig. 14. As for the two previously considered types of modern PE devices, the presented results indicate that the developed component-based PVI model is capable of correctly representing the power-dependent harmonic and waveform distortion characteristics for different operating and supply conditions.
Comparing the results in Figs. 14a and 14b shows an increase of distortion and a more pronounced ripple in the instantaneous ac current in very low power mode, while Fig. 14c demonstrates the inability of the PVI’s a-PFC circuit to control its output ac current in the presence of supply voltage distortion. The main reason for that is a relatively low gain of the PR current controller (adjusted to match the measured results for PVI-2), resulting in unstable operation due to the deviation of the controller output from the reference value in case of the distorted supply voltage. The shape of the PVI output current results from a trade-off in the control system, which is balancing the accuracy of the produced current control signal with the ability to maintain stable operation under the input filter resonances [21]. The unstable operation of PVI-2 is captured by the developed model, with Fig. 15 showing again a good matching of measurements and simulations for all considered waveform distortion indices.

G. On the Importance of Modelling Controls of PE Devices

Fig. 16 provides more details on the transfer of SMPS-2 from CCM to DCM operation (Section IV.B). As the SMPS power reduces, the modelled a-PFC control strategy (average current control) cannot maintain the inductor current above the zero value, even after increasing the frequency of switching. On the other hand, the modelled peak current control of the a-PFC circuit of EVBC-1 successfully maintains the inductor current between the upper and lower boundary, Fig. 17.

Fig. 17 also illustrates the complex behaviour of EVBC-1 as its operating power reduces from 100% to 10% of $P_{\text{rated}}$, and then to 4% of $P_{\text{rated}}$. Waveform distortion will first increase, due to pulse-like part in the middle of the half-cycle current waveform, but will then decrease, due to the alignment of the inductor current with the lower boundary.

Although both EVBC and SMPS contain a-PFC controlled front-end circuits, the EVBC has a more effective control. As a result, the harmonic characteristics presented to the network are considerably different, demonstrating the importance of the correct modelling of the a-PFC control for the evaluation of waveform distortion characteristics of modern PE devices.

V. CONCLUSIONS AND FURTHER WORK

Increasing numbers and installed powers of modern PE devices require careful assessment of their impact on both existing networks and future “smart grids”. Modern PE devices implement sophisticated controls, marking significant difference from the period as recent as one decade ago, when most PE equipment had only simple circuit topologies, without any PFC, or with only passive PFC circuit implemented in equipment design.

The results presented in this paper are limited in terms of the types and numbers of considered PE devices, as well as analyzed supply and operating conditions. Although further work is needed to identify and quantify possibly much wider range(s) of responses, the following conclusions can be drawn from the presented experimental and analytical evaluation.

Fig. 15. Comparison of measured (“meas”, hollow symbols) and simulated (“sim”, solid symbols) waveform distortion indices of PVI-2.

Fig. 16. SMPS inductor current and its reference waveform for WF1 and ZS1.

Fig. 17. EVBC inductor current and its reference waveform for WF1 and ZS1.
Most of the analyzed PE devices exhibit distinctive increase of relative harmonic emission in low power operating modes, which may become very high at very low powers. Two PVI and one EVBC also increased their absolute harmonic emission at low powers. This suggests that the impact of individual PE devices could increase if they simultaneously enter low power operating modes, e.g. due to daily variations of PVI outputs, or “smart grid” coordinated EVBC control. One example of a nuisance tripping of protection systems due to PVI operation in low power mode is given in [22].

For most (but not all) of the considered operating and supply conditions, the contribution of the fundamental current to the total current of a PE device will start to decrease at low powers, becoming equal to, or lower than the contribution of the non-fundamental current at very low powers. The two new indices introduced in this paper allow separate assessment of the contributions from the LF harmonics and other waveform distortions, highlighting that, in some cases, LF harmonics are not a main contributor to the total waveform distortion.

The presence of source impedance and supply voltage waveform distortion, which is typically the case in actual LV grids, might have a strong negative impact on performance of some PE devices (most evident for one of the tested PVI, which exhibits a six-fold increase of the THD values). This suggests that testing of modern PE devices should include non-sinusoidal waveforms, in order to check whether they can control harmonic emission in practical applications.

From the presented analysis, the main reason for increased waveform distortion of modern PE devices with a-PFC in low power operating modes is the transfer from CCM to DCM operation. This might be further pronounced if supply voltage distortions and source impedances are present, as some types of a-PFC will emulate the distorted input ac voltage waveform for setting internal current or voltage references. This clearly suggests that models of PE devices have to integrate control (a-PFC) circuits for correctly representing their characteristics.

Several lines of further work can be specified from the presented analysis. Regarding the experimental part, further tests with both individual and group-connected PE devices are required. Regarding the analytical part, evaluation of smart grid functionalities and wider area network studies will require the development of simplified general (“generic”) component-based models, to represent large numbers of same types of PE devices and their controls. When the modelled PE equipment features complex circuits and sophisticated controls (e.g. PVI and EVBCs), frequency domain modelling allows for a simpler and efficient representation of a large number of modelled devices (e.g. harmonic domain and harmonic state-space approaches). Work is in progress on both aspects (e.g. [23]).

APPENDIX A

### TABLE A.1 PARAMETERS OF SMPS, EVBC AND PVI MODELS

<table>
<thead>
<tr>
<th>SMPS-2</th>
<th>Input filter</th>
<th>Boost converter</th>
<th>Filter</th>
<th>CC-CV Charging Control</th>
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<td>C_{in}</td>
<td>μF</td>
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<table>
<thead>
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<th>DC-Link Volt.</th>
<th>PI Controller</th>
<th>Current PR Controller</th>
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### REFERENCES


