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Imposed Source Current Predictive Control for Battery Charger Applications with Active Damping

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Abstract

This paper presents an imposed source current control technique based on model predictive control. This proposed control method can be used for battery charger applications fed from three-phase ac grid. The proposed MPC technique allows to charge the battery with a constant current or voltage as what is required for cyclic charge process of batteries. The proposed technique ensures unity input power factor operation for grid side. The single-objective cost function of the predictive control employs the error between supply current reference and supply current prediction and the switching state that makes this user defined cost function minimal is selected among the nine switching vector combinations of the current source rectifier so as to apply for next sampling interval. An active damping current term, that is predicted from the input filter capacitor voltage estimation is included in the cost function to alleviate the resonance phenomenon of input LC filter. The supply current references in phase with grid voltages are generated from grid voltages and the amplitude of this reference currents are generated from the charging requirements of the battery. The input filter model is used to predict the filter capacitor voltages at sampling intervals k and k+1 in order to eliminate sensor requirement for them. The control performance of proposed predictive controller is validated by simulation works in terms of steady-state behavior, dynamic response and supply current THD.

Keywords: current source rectifier, battery charger, model predictive control, active damping

1. INTRODUCTION

The three-phase Current Source Rectifier (CSR) can be used as battery charger in electric vehicle and data center applications. LC filters are used for improving input and output current and voltage qualities by eliminating the unwanted frequency components.

In the control of CSRs, two main objectives are considered:

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1) To obtain unity power factor operation with low Total Harmonic Distortion (THD);

2) To regulate output voltage or current depending on applications.

The conventional control algorithm of CSR includes two control loops, one as an outer loop to regulate the output voltage and another one as an inner loop to control the output current. The control algorithm with the input filter compensation employs conventional space vector pulse width modulation (SVPWM) with six sectors to obtain regulated output voltage/current for load side and unity power factor with low THD for grid side. The Switching Loss Optimized (SLO) modulation scheme with 12-symmetric sectors has been used in order to reduce switching losses resulting in high converter efficiency [1]. In this rectifier, grid currents can be highly-polluted by any system harmonics as a result of resonance phenomenon of the LC filter placed at the input side of rectifier. To overcome this issue, active damping techniques are included in feedback control strategy of CSRs [2], [3].

The model predictive control (MPC) approach has emerged as an alternative to linear control techniques for power electronics topologies over the last decade [4]–[6]. MPC with imposed sinusoidal input currents is a technique for grid connected topologies such as direct matrix converters and current source rectifiers in order to obtain unity power factor operation. In this strategy the control algorithm imposes the converter to draw a source current having a sinusoidal waveform and being in phase with its respective source voltage [7], [8]. In [9], an MPC approach whose cost function employs dc link current and the supply currents in αβ coordinates has been proposed. Since the cost function includes two objectives, the use of weighting factor is unavoidable. This method requires the load model to predict the future load currents and requires the sector information for supply current space vector reference. In [10], a predictive control scheme, which is capable to operate the rectifier at very low switching frequency, has been proposed. Supply currents in αβ coordinates are predicted for next two sampling intervals using the input filter and converter models. Reference source currents are produced from the first harmonic components of the grid voltage. The amplitudes of these sinusoidal currents are derived from a DC load current error using a PI controller. A Phase Locked Loop (PLL) is employed to predict the supply voltages for next two sampling intervals. In [9], [10] active damping is not included in the proposed control techniques. In [11], a predictive control scheme for a CSR, that does not include output filter capacitor C_o, has been proposed and the cost function involves two terms; the first one is for minimizing reactive power drawn from the grid in order to obtain unity power factor and second term is responsible for the reference load current. Active damping current term is also added to the reference load current. The second term requires the load model to predict the load current at next sampling period. These two goals are combined into a single cost function with weighting factors. In [12], a model predictive PF control scheme for CSRs has been proposed to handle input Power Factor (PF) and LC resonance. The technique is based on the idea that reactive power reference estimator is used to obtain unity power factor and active damping method is adapted for LC resonance mitigation. But a lot of complexity is included for capacitive current compensation in order to eliminate the adverse effect of damping current on input PF regulation.

In this study, a model predictive scheme with active damping to simultaneously compensate the output control variable and input PF of a CSR is presented. The outline of the paper is as follows. The CSR topology and system model are defined in section 2. Proposed model predictive control is presented in section 3 and active damping technique associated with the control strategy is explained in section 4. The simulation results for proposed model predictive control are provided in section 5 in terms of input PF, supply current quality and reference tracking. The paper is concluded by section 6 describing the proposed control scheme and the results in brief.

2. SYSTEM AND PREDICTION MODELS

2.1. Current Source Rectifier Topology

The CSR, shown in Fig. 1, is a three-phase buck-type rectifier, which contains six unidirectional power switches. Output filter is usually used for eliminating high frequency component in order that output voltage and current will have better quality. The input LC filter is used for get rid of disturbances from three-phase ac grid. Due to constraints in the control of rectifier, there are only nine allowable switching vectors for this topology in which three of them are zero vectors.

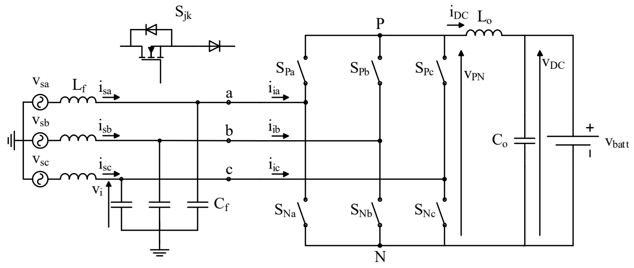


Figure 1. Current Source Rectifier

2.2. Rectifier Model

The output voltage, v_{PN}, and input current, $\mathbf{i_i}$, are given by (1) and (2).

$$\begin{aligned} v_{PN} &= \begin{bmatrix} S_{Pa}-S_{Na} & S_{Pb}-S_{Nb} & S_{Pc}-S_{Nc} \end{bmatrix} \begin{bmatrix} v_{ia} \\ v_{ib} \\ v_{ic} \end{bmatrix} \\ &= \mathbf{T_{CSR}} \mathbf{v_i} \end{aligned} \tag{1}$$

and

$$\begin{aligned} \begin{bmatrix} i_{ia} \\ i_{ib} \\ i_{ic} \end{bmatrix} &= \begin{bmatrix} S_{Pa}-S_{Na} & S_{Pb}-S_{Nb} & S_{Pc}-S_{Nc} \end{bmatrix}^T i_{DC} \\ \mathbf{i_i} &= \mathbf{T_{CSR}^T} i_{DC} \end{aligned} \tag{2}$$

where $\mathbf{T_{CSR}}$ is the instantaneous transfer function related to CSR topology. This transfer function can be used for describing different electrical quantities. The relationship between DC current and input current is defined in (2).

2.3. Prediction Model

In this work, input filter parameters are used to derive supply current prediction model, and input current and input voltage are measured to predict future behavior of supply current. The discrete-time model of input LC filter is defined in (3).

$$\begin{bmatrix} \mathbf{v_i}(k+1) \\ \mathbf{i_s}(k+1) \end{bmatrix} = \mathbf{\Phi} \begin{bmatrix} \mathbf{v_i}(k) \\ \mathbf{i_s}(k) \end{bmatrix} + \mathbf{\Gamma} \begin{bmatrix} \mathbf{v_s}(k) \\ \mathbf{i_i}(k) \end{bmatrix} \tag{3}$$

The filter model defined in (3) is used to calculate future value of supply current for the next time interval. Supply current prediction is given by (4) and filter capacitor voltage prediction is given by (5).

$$\begin{aligned} \mathbf{i_s}(k+1) &= \mathbf{\Phi}(2,1)\mathbf{v_i}(k) + \mathbf{\Phi}(2,2)\mathbf{i_s}(k) \\ &+\mathbf{\Gamma}(2,1)\mathbf{v_s}(k) + \mathbf{\Gamma}(2,2)\mathbf{i_i}(k) \end{aligned} \tag{4}$$

$$\begin{aligned} \mathbf{v_i}(k) &= \mathbf{\Phi}(1,1)\mathbf{v_i}(k-1) + \mathbf{\Phi}(1,2)\mathbf{i_s}(k-1) \\ &+\mathbf{\Gamma}(1,1)\mathbf{v_s}(k-1) + \mathbf{\Gamma}(1,2)\mathbf{i_i}(k-1) \end{aligned} \tag{5}$$

In order to reduce the number of required sensors, the input filter capacitor voltages at sampling interval k can be estimated using the measurements of supply voltages and currents at sampling interval k-1. In this case, input currents of the rectifier $\mathbf{i_i}$(k-1) are calculated from the optimal switching vector and measured output inductor current at sampling interval k-1. By this modification, the voltage sensors for input filter capacitors can be eliminated.

2.4. Battery Model

The resistance-capacitance battery model developed at National Renewable Energy Lab. of US is shown in Fig. 2. C_b is the main storage capacity and C_c is the fast charge-discharge capacitance. Values for these parameters are as following: C_b=82kF, C_c=4.074 kF, R_b=1.1 mΩ, R_c=0.4 mΩ and R=100 mΩ [13].

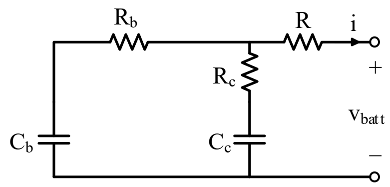


Figure 2. Battery Model

3. MODEL PREDICTIVE CONTROL

The proposed control approach is illustrated in Fig. 3. The supply voltage vector $\mathbf{v_s}$, supply current

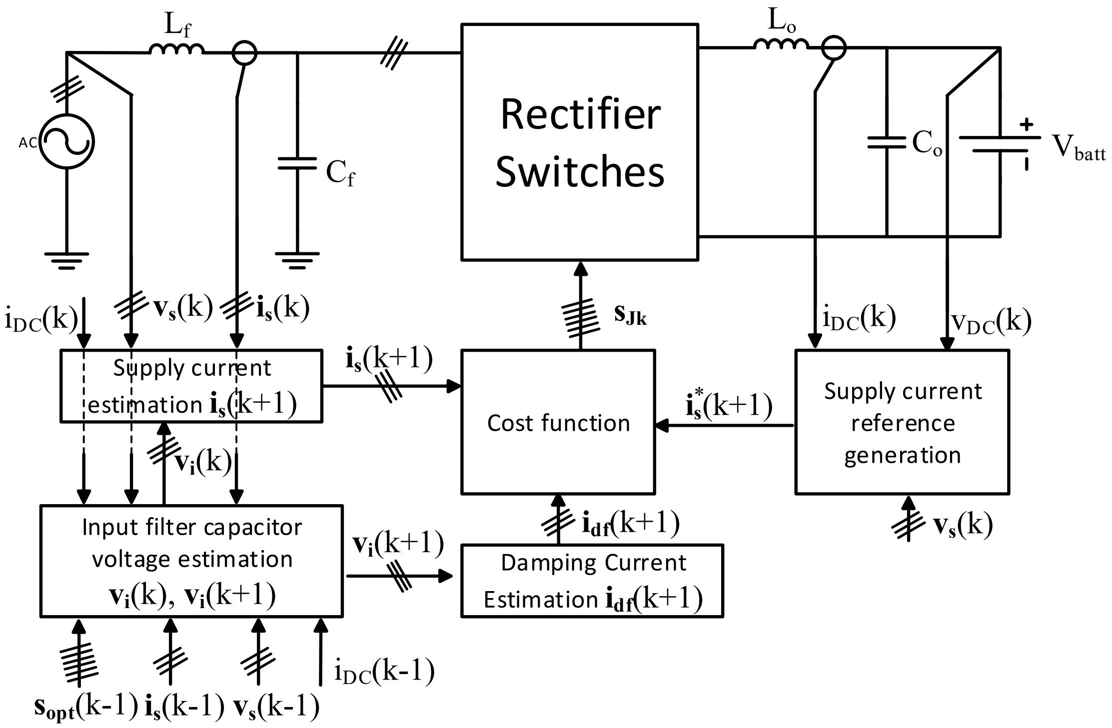


Figure 3. Model Predictive Control Scheme

vector $\mathbf{i_s}$, load voltage v_{DC}, and the output current i_{DC} are measured at instant k. These measurements are then used for the prediction of input filter capacitor voltages at instants k and k+1, and supply currents at instant k+1. Active damping term of the proposed control is included in model predictive control strategy and will be explained in the following section. The cost function defined in (6), where $\mathbf{i}_s^*(k+1)$ and $\mathbf{i}_s(k+1)$ reference and predicted supply currents respectively, calculates the error in supply currents with respect to corresponding supply current references which are generated in phase with grid voltages. The most critical point about cost function, any cost term related to the load is not introduced in this cost function. This is significant advantage for controlling the system under unknown load condition. The best switching states that minimizes the user defined cost function, see Eq. (6), is applied to the CSR system. This iterative technique is repeated in every sampling step.

$$g = \sum_{j=a,b,c} \left| i_{sj}^*(k+1) - i_{sj}(k+1) \right|^2 \tag{6}$$

In order to generate sinusoidal supply current references in phase with grid voltages, this paper uses the reference generation block shown in Fig. 4. In a cyclic charge process, the battery is either charged by a constant current (CC) or a constant voltage (CV). According to CC or CV charging, the reference charge current or voltage are assumed to be known and these reference commands can be used to generate a constant, m, which is used as a multiplier to convert the supply voltage measurements to current references. In order to eliminate the steady-state errors in charge current or charge voltage, two PI compensators are added to this control scheme. If the battery is charged by CV, the error between reference charge voltage and output voltage v_{DC} is fed to a PI compensator in order to generate a current reference and then another PI compensator, that is fed by error in charge current, is used to generate the constant, m.

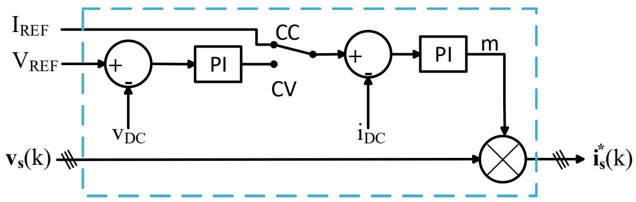


Figure 4. Supply current reference generation block

4. ACTIVE DAMPING

Since the input LC filter of a CSR is lightly damped, resonance mode of this filter can be excited by any harmonic that interferes from the utility or the rectifier itself and this results in highly polluted grid currents [3]. A damping resistor placed parallel to the input filter capacitor can be used to mitigate this resonance at the expense of a large drop in efficiency. In order to increase the efficiency to a reasonable level, the function of a resistance can be emulated by the rectifier, which is called active damping. Active damping forces the rectifier to draw a current proportional to the filter capacitor voltage. The dc component of the damping current causes an active power flow to the rectifier and has an adverse effect on the active power control. A simple High Pass Filter (HPF) can be used to filter the dc component of the damping current and allows the passage of the fundamental component.

Since the imposed source current method was adopted in MPC scheme of this study, the active damping technique was considered slightly different from the above conventional active damping. Instead of forcing the rectifier to draw high pass filtered current terms, which is proportional to the filter capacitor voltage, these currents were injected into the sinusoidal supply current references. To avoid distorting the active and reactive power components drawn from the grid, dc and fundamental components of these currents must be eliminated using an HPF.

Active damping scheme is depicted in Fig. 5. Since the MPC has a predictive nature, the estimated values for sampling time interval of k+1 are used in this scheme. Input filter capacitor voltage at sampling interval of k+1 is estimated using the one-step ahead shifted version of (5). This estimated value is then employed in (7) to calculate damping current term $\mathbf{i_d}$(k+1). An HPF, whose 3-dB bandwidth is set to 600 Hz, is used to alleviate dc and fundamental components of the damping currents and to generate the filtered version of damping current term, $\mathbf{i_{df}}$(k+1). In this paper a simple first-order HPF is used. If an HPF with a sharper frequency response (with a stopband of 80 Hz and passband of 100 Hz) is used, a better active damping effect can be achieved to eliminate the third and fifth order components. The transfer function of the HPF in continuous time is given in (8) and discrete version of the filter is provided in (9). The filtered damping current term is then included in the modified cost function as given by (10) in order to inject damping current term into sinusoidal references.

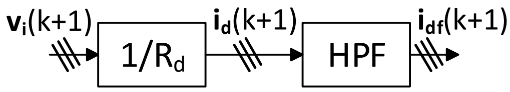


Figure 5. Damping current estimation scheme

$$\mathbf{i_d}(k+1) = \frac{\mathbf{v_i}(k+1)}{R_d} \tag{7}$$

$$HPF(s) = \frac{2.6526e\text{-}04s}{1 + 2.6526e\text{-}04s} \tag{8}$$

$$\mathbf{i_{df}}(k+1) = 0.8115\,\mathbf{i_{df}}(k) + \mathbf{i_d}(k+1) - \mathbf{i_d}(k) \tag{9}$$

$$g = \sum_{j=a,b,c} \left| i_{sj}^{*}(k+1) + i_{dfj}(k+1) - i_{sj}(k+1) \right|^2 \tag{10}$$

5. SIMULATION RESULTS

In order to validate the functionality of the proposed framework, several simulation works are performed. All simulation works are done by using Matlab/Simulink. Table 1 lists the parameters used in simulation study.

Table 1. Simulation Parameters

Parameter	Description	Values
T_S	Sampling Period	50 µs
R_d	Damping Resistance	50 Ω
L_o	Output Inductance	10 mH
L_o	Output Inductance	10 mH
C_o	Output Capacitance	100 µF
L_f	Input Inductance	2 mH
C_f	Input Capacitance	120 µF
R_f	Inp. Filt. Damp Resistance	1 Ω
V_s	Supply Peak Voltage	100 V

The results presented in Fig. 6 are obtained when CC charging is used for reference generation. Fig. 6 shows supply voltage and current for phase-a, output current of the rectifier i_{DC} and supply power components for the case in which a 90V-battery is charged from the grid according to the predefined charge current reference command. As it is observed from Fig. 6, the proposed control scheme ensures unity power factor operation and achieves good reference tracking. When CC charging is used for reference generation, the average switching frequency is measured as 3.06 kHz for 90V – 10A battery charging experiment whereas it is measured as 2.65 kHz for 90V – 5A battery charging experiment.

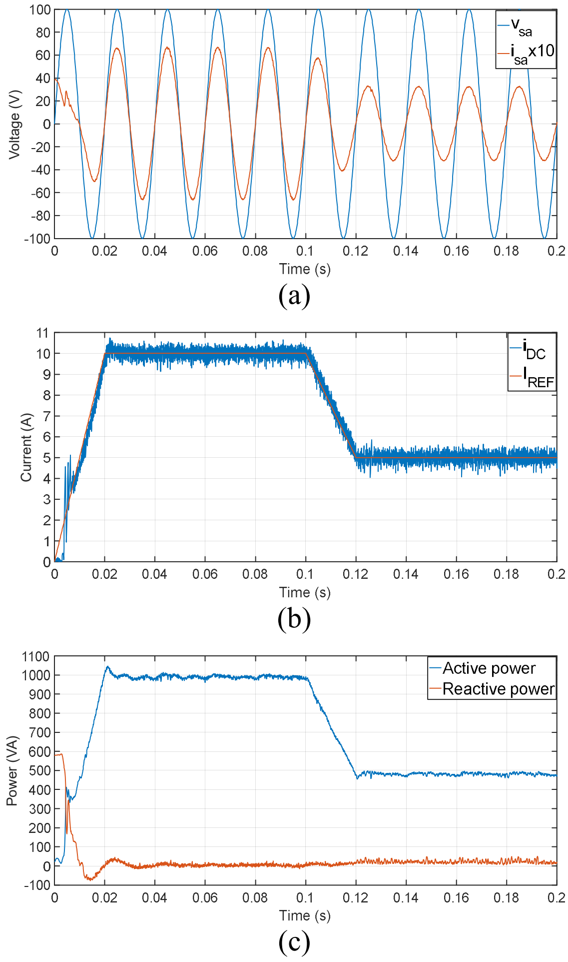


Figure 6. Waveforms for 90V-battery charge and reference generation with PI compensator according to CC charging; (a) Supply voltage and current (x10) for phase-a, (b) charge current command and output current, (c) supply power components

Fig. 7 shows the results of the FFT analysis of the grid current for the case where a 90V-battery is charged with 5A. The total harmonic distortion (THD) in grid current is 4.70% when the damping current term is not included in the cost function whereas THD is decreased to 2.11% with inclusion of damping current term. Comparison results in terms of supply current THD for different operating points are tabulated in Table 2. Although the THD results for the high sampling time are higher as expected, the contribution of the active damping term on THD is more noticeable for low charge current levels at higher sampling periods.

Table 2. THD results obtained under different charge current, battery voltage and sampling period when CC charging is used for reference generation

Sampling Period ↓	V_{batt} →	48V		90V	
	I_{REF} →	5A	10A	5A	10A
	Control↓				
Ts=50µs	without damping	4.38%	2.21%	4.70%	1.78%
	with damping	2.24%	1.56%	2.11%	0.88%
Ts=100µs	without damping	13.09%	5.52%	11.78%	5.25%
	with damping	6.96%	5.17%	8.10%	3.75%

Kp=0.0001, Ki=10 @TS=50µs, Ki=1 @TS=100µs

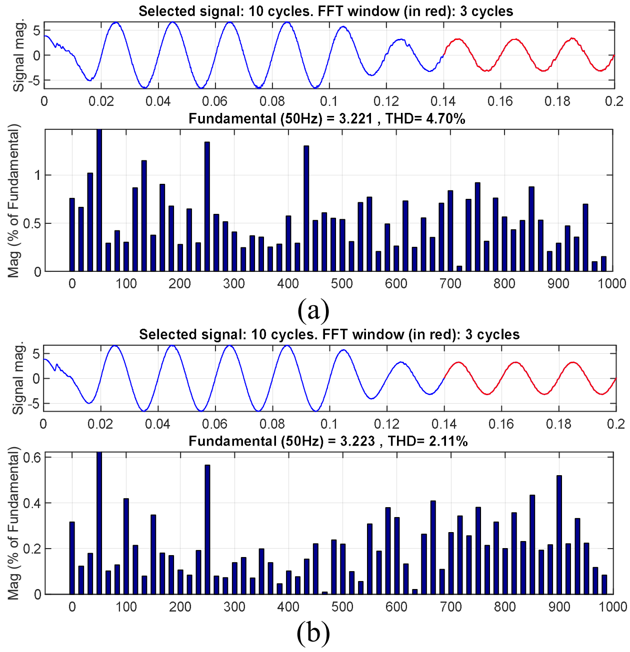
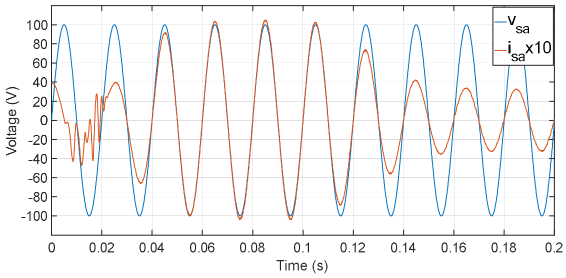


Figure 7. FFT analysis for supply current for V_{batt}=90 V and I_{REF} =5A; (a) without active damping, (b) with active damping.

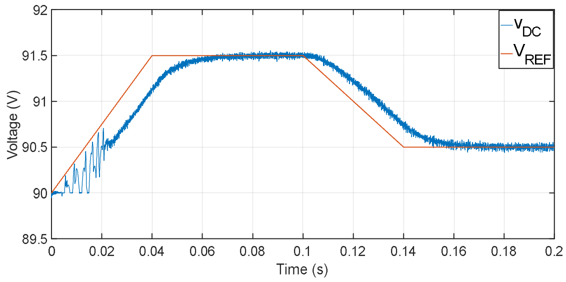
The results presented in Fig. 8 are obtained when reference generation according to CV charging is used. The unity power factor operation with low THD at grid side is still achieved while the output voltage reference tracking is quite stable.

6. CONCLUSION

In proposed control method, model predictive strategy is presented to simultaneously control the output variable and input PF of a CSR that is used in a three-phase grid to battery charger application. In the control scheme, the filter capacitor voltages and supply currents are predicted using system



(a)



(b)

Figure 8. Waveforms for 90V-battery charge and reference generation with PI compensator according to CV charging; (a) Supply voltage and current (x10) for phase-a, (b) Reference charge voltage and output voltage, v_{DC}

model. The sensors measuring the input filter capacitor voltages are eliminated by predicting these voltages from other measurements on the system. The cost function of MPC employs the errors between sinusoidal supply current references and supply current predictions in abc-frame. The cost function is evaluated for all possible switching combinations of the CSR and one that minimizes this cost function is selected and applied to the rectifier for next sampling interval. Sinusoidal supply current references are generated from supply voltages using nested two PI compensators which are fed by errors in charge current or voltage. Active damping method is included into the predictive control scheme in order to mitigate resonance at supply side. High pass filtered active damping current term is added to cost function to force the rectifier to draw a current that has high frequency components responsible to alleviate adverse effect of input filter resonance. As a result, the THD in grid currents are reduced. The proposed method enables the battery to be charged with reference current or voltage according to the charging requirement, simultaneously guarantees the unity PF operation at the grid side and minimizes the THD by active damping method.

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