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# Control of a charging station for electric vehicles

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**Abstract.** A weighted average current control applied to a three-phase inductor-capacitor-inductor grid-connected battery charger for electric vehicles is presented in this paper. The proposed controller is based on a combination of the partial currents of the system (inverter and grid currents), which are feedback into the control loop. Therefore, by using this approach a reduction of the system order is achieved. The proposed controller allows a bidirectional control of the converter currents, thus allowing both, a controlled charge of the battery and the injection of the current with low distortion in the grid. Further, the implemented controller does not needs to measure the inverter currents. The control strategy is validated with simulation results.

## 1. Introduction

In recent years, interest in electric vehicles (EV) has increased because they constitute a very efficient alternative to reduce greenhouse gases produced by internal combustion vehicles. EV use electric energy for their operation, which is supplied by an on-board battery bank (BB). The BB can be recharged through a grid-connected battery charger (BC) which can be on-board or off-board [1–4].

The off-board BC, also known as charger stations, constitute the key to supply energy to EV in public areas and in a short time. A possible configuration for a BC is a three-phase inverter connected to the grid through a proper filter. It is also desirable that this system be able to work with bidirectional power flow [5–8].

The filters for grid connection can be inductive (L-filter) or a combination inductor-capacitor-inductor (LCL-filter), among others. The use of LCL filters is growing in last years due to they allow a better attenuation of the harmonic current content. Nevertheless, the use of LCL filters increase the system order, while they are susceptible to interferences and resonance effects. To solve these problems advanced control strategies should be considered [9–12].

In this work, a control strategy for a three-phase BC connected to the grid through an LCL filter is presented. Due to the high order of the system (ninth-order), a weighted average current control (WACC) is proposed with the objective of reducing the order through the feedback of the sum of the partial inverter and grid currents [10, 13, 14]. Also, by a combination of the dynamic equations, a reduction of the needed measurements is achieved and only the grid currents and grid voltages should be measured for the implementation of the controller.

Due to the aforementioned advantages, this proposal aims to contribute to the development of charging infrastructure for EVs both locally and globally, to solve the energy problems that may be generated when several VEs are connected to the existing power electrical system, contributing also to the reduction of the environmental pollution. The control strategy is validated with simulation results using a realistic model of the system.

## 2. Weighted average current control for a three-phase battery charger with inductor-capacitor-inductor filter

### *2.1. Modeling of the voltage source converter*

The studied system, shown in Figure 1, is composed of a three-phase inverter connected to the grid through an LCL filter with a DC-Link connected to the battery bank. The dynamic of the system in Equation (1), is obtained using the *abc* to *dq* transformation.

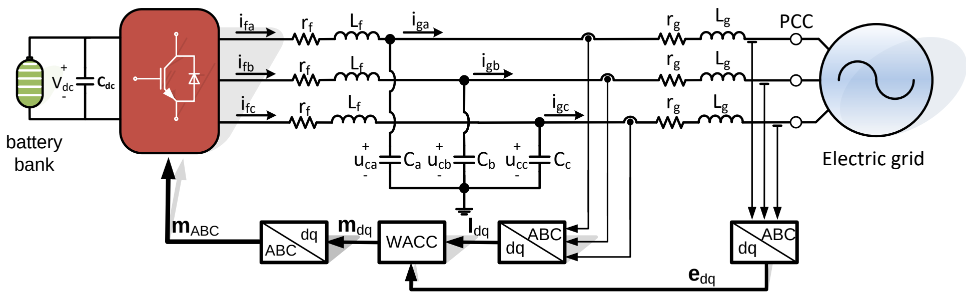


**Figure 1.** Grid connected LCL three-phase inverter.

$$
\begin{aligned}
L_f \frac{d\,\mathbf{i}_{fdq}}{dt} &= -\left(R_f + \omega_{dq}\mathbf{J}L_f\right)\mathbf{i}_{fdq} - \mathbf{u}_{cdq} + \mathbf{v}_{dc}\mathbf{m}_{dq}, \\
L_g \frac{d\mathbf{i}_{gdq}}{dt} &= -\left(R_g + \omega_{dq}\mathbf{J}L_g\right)\mathbf{i}_{gdq} + \mathbf{u}_{cdq} - \mathbf{e}_{gdq}, \\
Cd\frac{\mathbf{u}_{cdq}}{dt} &= -\omega_{dq}\mathbf{J}C\mathbf{u}_{cdq} + \mathbf{i}_{fdq} - \mathbf{i}_{gdq},
\end{aligned} \quad (1)
$$

where $\mathbf{i}_{fdq}$ and $\mathbf{i}_{gdq}$ are the inverter and grid currents vectors, respectively, $\omega_{dq}$ is the reference frame frequency, $\mathbf{J}$ is an anti-symmetric matrix, $\mathbf{u}_{cdq}$ is a vector with the capacitor voltages, $\mathbf{e}_{dq}$ is a vector with the grid currents, $R_g$ and $R_f$ represent the resistive losses in the inductor filter, $L_f$ y $L_g$ are the inductances of the filter and finally $\mathbf{m}_{dq}$ is a control signals vector.

### *2.2. Weighted average current control*

The proposed WACC for the three-phase BC connected to the grid through an LCL filter allows an order reduction in the system dynamics, thus transforming a ninth-order system into a first-order one. This controller also allows increasing the bandwidth of the system response and the control loop gain. With this method, the weighted value of the currents is obtained through a sum of the equations that govern the system dynamics in *dq* coordinates.

By defining an average factor as $\frac{L_f}{L_f+L_g}$ and $\frac{L_g}{L_f+L_g}$ for the currents $\mathbf{i}_{fdq}$ and $\mathbf{i}_{gdq}$ respectively, it can be obtained a current $\mathbf{i}_{wa}$ which is the average of the circulating currents in the inductors of LCL filter. Thus, this control strategy is named WACC. In this way, the weighted average current is defined as in the Equation (2).

$$
\mathbf{i}(t)_{wadq} = \frac{L_f\ \mathbf{i}(t)_{fdq}}{L_f + L_g} + \frac{L_g\ \mathbf{i}(t)_{gdq}}{L_f + L_g}. \quad (2)
$$

If the Laplace transformation is applied to Equation (1), the combination defined by Equation (2) is performed and $k = \frac{R_f}{L_f} = \frac{R_g}{L_g}$ is defined, the weights for the currents are obtained as in the Equation (3).

$$\begin{aligned}(s+k)\left(\frac{L_f I(s)_{fd} + L_g I(s)_{gd}}{(L_f+L_g)}\right) &= \frac{\omega_{dq}\left(L_f I(s)_{fq} + L_g I(s)_{gq}\right)}{(L_f+L_g)} + \frac{m_d V(s)_{dc} - e(s)_{gd}}{(L_f+L_g)},\\ (s+k)\left(\frac{L_f I(s)_{fq} + L_f I(s)_{gq}}{(L_f+L_g)}\right) &= \frac{-\omega_{dq}\left(L_f I(s)_{fq} + L_g I(s)_{gq}\right)}{(L_f+L_g)} + \frac{m_d V(s)_{dc} - e(s)_{gq}}{(L_f+L_g)}.\end{aligned} \tag{3}$$

By renaming the terms of Equation (3), the equations of weighted average currents results in Equation (4).

$$(s+k)\,\mathbf{I}(s)_{wadq} = \frac{V_{dc}\left[\mathbf{m}_{dq} + \frac{(L_f+L_g)}{V_{dc}}\omega_{dq}\mathbf{J}\ \mathbf{I}(s)_{wadq} - \frac{e(s)_{gdq}}{V_{dc}}\right]}{(L_f+L_g)}. \tag{4}$$

For a simplification in the analysis and design of Equation (4) a new variable $\mathbf{m}'_{dq}$ is defined Equation (5).

$$\mathbf{m}'_{dq} = \mathbf{m}_{dq} + \frac{(L_f+L_g)}{V_{dc}}\omega_{dq}\mathbf{J}\ \mathbf{I}(s)_{wadq} - \frac{\mathbf{e}(s)_{gdq}}{V_{dc}}, \tag{5}$$

Thus, by replacing Equation (5) in Equation (4) results Equation (6).

$$(s+k)\,\mathbf{I}(s)_{wadq} = \frac{V_{dc}}{(L_f+L_g)}\mathbf{m}'_{dq}. \tag{6}$$

These considerations allow finding in the Equation (6) a first-order transfer function that simplifies the control design, Equation (7).

$$G(s)_{wadq} = \frac{\mathbf{I}(s)_{wadq}}{\mathbf{m}'_{dq}} = \frac{V_{dc}}{s(L_f+L_g)+(R_f+R_g)}. \tag{7}$$

In Figure 2 a scheme of the proposed control strategy is presented, where $\mathbf{i}_{wadq}$ are the feedback of the averaged currents and $\mathbf{i}^*_{wadq}$ are the desired values. The controllers are proportional-integral (PI) realizations, $G_{pi} = K_p(s + \frac{K_i}{K_p})/s$, whose parameters are designed using a root-locus method.

For the implementation of the proposed controller the value of $\mathbf{m}_{dq}$ (see Equation (8)) is obtained from the Equation (5) (see Figure 2).

$$\mathbf{m}_{dq} = \mathbf{m}'_{dq} - \frac{(L_f+L_g)}{V_{dc}}\omega_{dq}\mathbf{J}\mathbf{I}(s)_{wadq} + \frac{\mathbf{e}_{gd}}{V_{dc}}. \tag{8}$$

To become independent of the measurement of $\mathbf{i}_{fabc}$, a combination of the system equations is performed, obtaining $\mathbf{i}_{fdq}$ as functions of $\mathbf{i}_{gdq}$ and $\mathbf{e}_{gdq}$. Then, from Equation (1) results Equation (9).

$$
\begin{aligned}
I(s)_{fd} &= (s^2CL_g + sR_g - \omega_{dq}^2 CL_g + 1)I(s)_{gd} + (2s\omega_{dq}CL_g + \omega_{dq}CR_g)I(s)_{gq} \\
&\quad + sCe(s)_{gd} + \omega_{dq}Ce(s)_{gq}, \\
I(s)_{fq} &= -(2s\omega_{dq}CL_g + \omega_{dq}CR_g)I(s)_{gd} + (s^2CL_g + sR_g - \omega_{dq}^2 CL_g + 1)I(s)_{gq} \\
&\quad + \omega_{dq}Ce(s)_{gd} + sCe(s)_{gq}.
\end{aligned} \tag{9}
$$

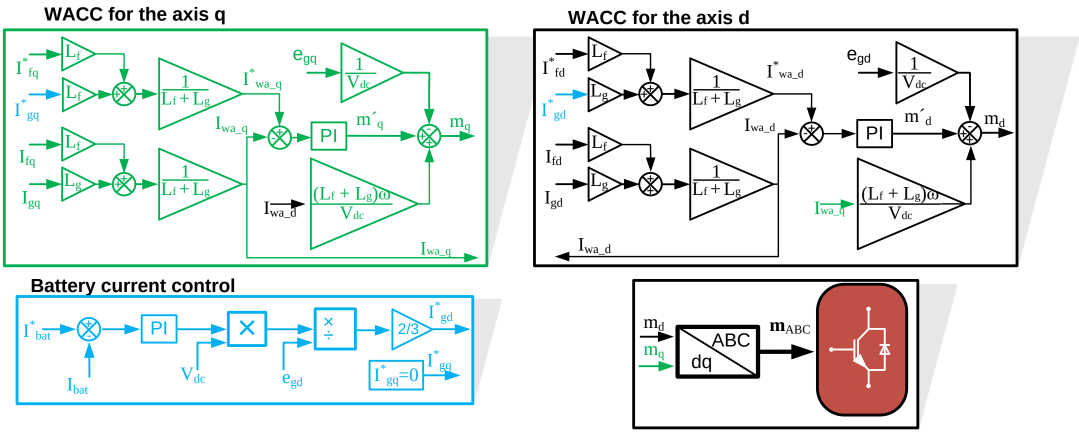


**Figure 2.** Scheme of the proposed WACC.

### *2.3. Simulation results*

The desired specifications for the system are: settling time, $t_s < 0.02$ s and maximum overshoot OS% $\leqq$ 20% . The desired performance is achieved with $K_P = 0.0013579$ and $K_i = 2.1145299$. The proposed control strategy was validated through simulation tests using SimPowerSystem from Matlab. The system parameters are: grid voltage $v_{LLrms} = 155$ V, battery voltage $V_{dc} =$ 400 V and the LCL filter parameters $L_f = 1.25e^{-3}H$, $L_g = 0.625e^{-3}H$, $R_f = 0.2$ and $R_g = 0.1$.

Through the control of the battery current (see Figure 2), from Equation (10) and Equation (11), the reference of the grid current is calculated. By replacing $i_{gd}$ and $i_{gq}$ by $i^*_{gd}$ and $i^*_{gq}$ in Equation (9), respectively, $\mathbf{i}^*_{fdq}$ is obtained. With the current references and Equation (2), $\mathbf{i}^*_{wadq}$ is obtained.

$$P = \frac{3}{2}\left(i_{gd}e_{gd} + i_{gq}e_{gq}\right),\ Q = \frac{3}{2}\left(i_{gd}e_{gq} - i_{gq}e_{gd}\right). \tag{10}$$

$$P = \frac{3}{2}\left(i_{gd}e_{gd}\right) = I_{bat}V_{DC} \rightarrow i_{gd} = \frac{2}{3}\frac{I_{bat}V_{DC}}{e_{gd}},\ i_{gq} = 0. \tag{11}$$

Figure 3(a) shows the battery current in this case. It can be observed that $i_{bat}$ goes from a negative value (charge of the battery) to a positive value (discharge of the battery). The change is produced at 0.2 s and the system begins to inject current into the grid at this moment. In Figure 3(b) the current and voltage of phase $a$ are shown. Before the change (0.2 s) the phase between voltage and current is 180° and after the change it is 0°. In Figure 3(d) the state of charge of the battery is shown, while Figure 3(e) shows the grid current in $dq$ coordinates. Finally, in Figure 3(c) and Figure 3(f) the total harmonic distortion (THD) for both states (charge and discharge) is presented. As can be see, in both cases the obtained THD is below of the standard limits (5%).

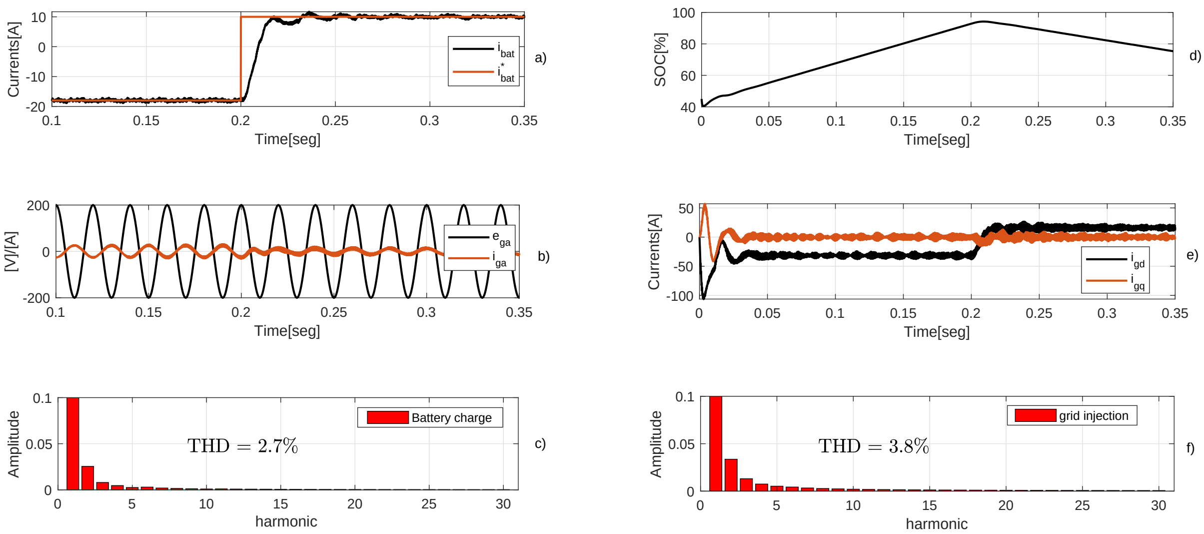


**Figure 3.** Simulation results of the three-phase charging station. (a) Battery current, (b) current and voltage of phase a, (d) the state of charge of the battery, (e) grid current in dq coordinates, (c) and (f) THD.

## 3. Conclusions

In this work, a WACC control for three-phase battery charger with LCL filter (charger station for electric vehicles) was presented. The proposed control allows a reduction of the system order resulting in a first-order one which simplifies the control design, thus allowing the use of the classic PI controllers. It also allows to increase the bandwidth and the controller gains, achieving a better performance. Working with the systems equations, the measure of the inverter currents was avoided, being only necessary the measurement of the grid voltages and currents for implementing the controller. The performance of the controller was validated through simulation tests, which showed the correct performance for both stages, charging and discharging the battery. The THD of the grid current in both stages was maintained below the standard limits.

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