A DIRECT DISCRETE-TIME OUTPUT FEEDBACK-BASED LS-RMRAC FOR GRID-TIED CURRENT CONTROL LOOP OF A STATIC 3-WIRE CONVERTER UNDER UNBALANCED GRID VOLTAGE CONDITIONS.¹

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ABSTRACT

Nowadays, renewable energy generation is a worldwide tendency. These clean sources are generally tied to the grid by voltage-fed static converters. In this work, a direct discrete-time Output Feedback-based LS (Least Squares)-RMRAC (Robust Model Reference Adaptive Control) is proposed for grid-side current loop control of a static 3-wire converter connected to the grid through LCL filter. The proposed control method mitigates the LCL filter resonance, rejects grid disturbances without needing Resonant Controllers implementation, and deals properly with grid uncertainties and parametric variations, being suitable for grids with unbalanced voltage conditions. Simulation results of proposed controller are presented.

Keywords: Robust Adaptive Control. Grid-tied converter. LCL filter.

1 Introduction

Nowadays, fast society progress and growing industrial production have been demanding more and more energy. However, by use of conventional power generation, fossil fuels quickly will be shortened (FANG et al., 2019). Due to it and the global warming concerns, there is an increasing investment on renewable energy systems, such as: solar and wind farms, biomass power plant and ocean wave energy installations (ELSAYAD; MORADISIZKOOGHI; MOHAMMED, 2018). However, even with all progress, there are still many remote locations in the world, which do not have access to electricity, or if have, it is a very restricted time connected in the grid (TIWARI; SINGH; GOEL, 2018). Moreover, a great portion of these places are rich in clean energy sources, which can be used to supply these remote areas sustainably through stand-alone power systems (NEHRIR et al., 2011).

Currently, there are over 400 GW of renewable energy generation worldwide, being around 300 GW by wind power and 100 GW by photovoltaic generation (ISLAM; GUO; ZHU,
2013). It is highlighted that renewable energy-based stand-alone power systems of more than 10 MW in capacity, each power plant, already became a reality (ISLAM; GUO; ZHU, 2012). Therefore, renewable energy generators and distributed loads have emerged as an appealing solution for global development (RAHBAR; CHAI; ZHANG, 2016), from industrial requirements to remote village citizens needs. Thereby, power generation from renewable energy sources are becoming more and more pervasive in the energetic matrix (CRAMER et al., 2019).

Generally, power electronic converters are used to integrate primary source to the grid, and properly regulating the output power (KHWAN-ON; KONGKANJANA, 2017), with filters to reduce harmonics from converter switching. The two most popular filters used to interface grid and converter are L and LCL filters. Although L filter has a simpler structure and it is easier to design using active damping techniques, its major drawback is the reduced harmonics reduction in comparison to the LCL filter. Besides, LCL filter has reduced weight and size than L filter (TEODORESCU; LISERRE; RODRÍGUEZ, 2011). Moreover, LCL filter is cheaper; it allows lower switching frequency and has less reactive power consumption in the grid fundamental frequency (DANNEHL; FUCHS; THØGERSEN, 2010). In this work, a static 3-wire converter is simulated connected to the grid by an LCL filter.

The main drawback of the LCL filter is its resonance peak, which can cause controller performance degradation, and more, it can turn unstable the current loop control. In the literature, there are many approaches to mitigate LCL resonance peak by active damping. Among them, PI (Proportional Integral) controller (LINDGREN; SVENSSON, 1998; DANNEHL et al., 2010), virtual resistance-based PI controller (MOHAMMADI et al., 2019), PI plus repetitive controller (GAO et al., 2018), Optimal controller (MACCARI et al., 2015; TRAN; YOON; KIM, 2018), robust controller (OSÓRIO et al., 2019; GONZALEZ; BUSADA; SOLSONA, 2020), predictive controller (BOSCH; STAIGER; STEINHART, 2017; NAM et al., 2021), and others.

In general, fixed-gain controllers showed excellent performance only when the grid had no inductance changes (from strong to weak conditions), and the phases were equilibrated. However, grid inductance is always changing in practice, and their phases are not perfectly balanced, being necessary to use multi-loop fixed-gain control strategies to ensure energy quality. Alternatively, robust controllers designed with polytopic models can deal with grid uncertainties without multi-loop control laws, as proposed on (MACCARI et al., 2013; OSÓRIO et al., 2019; JUNIOR et al., 2020; BELOV, 2022). These controllers presented high performance in the current control, even when the grid was unbalanced. However, the design of this kind of controller requires a lot of experience with LMI (Linear Matrix Inequalities), which is a non-trivial technique. Furthermore, the performance of a robust controller is highly dependent on the plant model. Thereby, although these methods have presented good performance on grid-
injected current control at non-nominal conditions, the main drawback for all is the same: their gains are fixed values. This characteristic restricts their operational point and do not guarantee performance for parametric variations outside designed operational range (FLORA; GRÜNDLING, 2008). Therefore, in this work is presented an adaptive controller solution, which can properly deal with variable operational points and more, it can deal with exogenous disturbance from the grid without needing Proportional Resonant controllers, avoiding multi-loop controllers. The proposed strategy to control grid-side currents of a static 3-wire converter is a direct discrete-time Output Feedback-based LS (Least Squares)-RMRAC (Robust Model Reference Adaptive control). Simulation results including converter switching, implementation delay, voltage grid synchronization and pulse width modulation through Space Vector method are presented to validate the controller performance. Besides, voltage grid synchronization is performed with a Kalman filter, eliminating the need for using a conventional phase-lock loop. Moreover, parametric variations in grid impedance and unbalanced grid voltage conditions are also considered.

This work is organized as follows: Section II gives the mathematical model of a grid-tied static 3-wire converter with LCL filter. Next, in the Sections III and IV are presented controller design and simulation results, respectively. Lastly, in Section V, the final considerations of this work are presented.

2 Grid-tied Static 3-wire Converter with LCL filter

A renewable energy power system consists of four main subsystems: a clean power source generator (generally sun, wind, ocean waves, or biomass), a power converter, a capacitor bank, and AC filter. In the simulations, the clean power source was approximated to a continuous-voltage source, \( V_{CC} \), which can represent the sun in a photovoltaic system. In addition, the electrical grid was assumed to be predominantly inductive, modeled by a sinusoidal source \( V_d \), as presented Figure 1. The grid impedance is represented by inductance \( L_g \) and parasitic resistance \( R_g \), in series with the grid, \( V_d \). Besides, the LCL circuit was represented by the Thevenin equivalent in relation to the PCC (Point of Common Coupling) (TAMBARA et al., 2017). The LCL parameters, shown in Figure 1, are: \( i_c, v_c \) and \( i_g \), which are converter-side currents, capacitor voltage and grid-side currents, respectively. It is noteworthy to emphasize that total grid-side inductance and total grid-side resistance are given by \( L_g = L_{g1} + L_{g2} \) and \( R_g = R_{g1} + R_{g2} \), respectively. Also, \( R_c \) and \( L_c \) are the converter resistance and inductance, respectively.

It is known that resulting model in three-phase coordinates is coupled and design an active damping method for it is a hard and complex task (EVALD; TAMBARA; GRÜNDLING,
Therefore, Clarke Transform (DUESTERHOEFT; SCHULZ; CLARKE, 1951) was applied on three-phase coordinates model, obtaining two identical decoupled single-phase linear time-invariant (LIT) models (TAMBARA et al., 2017), which are equivalent and preserve current and voltage amplitude. Note that, if grid phases are equilibrated, then there is no path for current conduction on the 0 axis; therefore, it can be disregarded. However, here, the grid is considered unbalanced; thence, there will be current flowing in the 0 axis. In this situation, a fixed-gain controller does not guarantee good performance and stability; once, for a 3-wire converter, it has no access to control 0 axis. However, it is shown that even under these unfavorable conditions, and more, considering parametric variation in one of the grid phases, the proposed controller is robust enough to maintain the closed-loop system stable, with small tracking error, which is feasible for experimental implementation. The transfer function, \( G(s) \), of identical decoupled models in \( \alpha\beta \) coordinates, taking into account that the converter is disconnected from the grid \( v_d = 0 \), because the grid is the exogenous disturbance for the current controller, is given by

\[
G(s) = \frac{i_g(s)}{u(s)} = \frac{1}{s^3 + \frac{(R_g L_c + R_c L_g)}{L_g L_c} s^2 + \frac{(L_c + L_g + R_g R_c)}{L_g L_c} s + \frac{R_g + R_c}{L_g L_c}}
\]

where \( u(s) \) is the voltage synthesized by the converter through Space Vector Modulation (SVM) technique. Moreover, implementation delay was considered in the simulation. To do it, the control action is implemented with a delay of 1 time step, that is, \( u(k) = u(k - 1) \).

3 Direct Discrete-time Output Feedback-based LS-RMRAC

First of all, assuming that a continuous-time plant was properly discretised, a discrete-time SISO (Single Input Single Output) plant \( G(z) \) can be described as

\[
G(z) = G_0(z)[1 + \mu \Delta_m(z)] + \mu \Delta_n(z),
\]

where \( \Delta_m(z) \) and \( \Delta_n(z) \) are the modeling and parametric uncertainties, respectively. The controller design can be achieved using a combination of LS-RMRAC (Least Squares Robust Model Reference Adaptive Control) and output feedback. The control law can be expressed as

\[
u_k = -k u_{k-1} + \sum_{i=0}^{N-1} a_i s_i y_{k-i} + \sum_{i=0}^{M-1} b_i s_i \hat{y}_{k-i}
\]

where \( s_i \) are the reference signals, \( y_k \) is the system output, \( u_k \) is the control input, \( a_i \) and \( b_i \) are the controller parameters, and \( N \) and \( M \) are the delays in the reference and output signals, respectively.
where $\Delta_m(z)$ and $\Delta_u(z)$ are a multiplicative and an additive dynamics, respectively (EVALD; TAMBARA; GRÜNDLING, 2020b). Also, $G_0(z)$ is the modeled part of the plant, which is described by

$$G_0(z) = k_p \frac{Z_p(z)}{R_p(z)},$$

(3)

where $k_p$ is the high frequency gain of $G_0(z)$, $Z_p(z)$ and $R_p(z)$ are monic polynomials of degrees $m$ and $n$, respectively.

The additive and multiplicative dynamics jointly with modeled part of the plant must satisfy the following assumptions (IOANNOU; SUN, 2012),

A1) $Z_p(z)$ is a Schur polynomial and the high frequency gain signal is known;
A2) $\Delta_u(z)$ is a strictly proper Schur transfer function, and $\Delta_m(z)$ is a Schur transfer function;
A3) The upper bound on stability margin of $\Delta_u(z)$ and $\Delta_m(z)$ is internal to the unit Z circle.

In reference model-based adaptive controllers, it does not track the reference signal directly; that is, the plant output is forced to track the reference model output, as close as possible. The reference model, $W_m(z)$, is designed with the same relative degree of $G_0(z)$ as follows

$$y_m = W_m(z)r = k_m \frac{Z_m(z)}{R_m(z)}r,$$

(4)

where $k_m$ is the high frequency gain of $W_m(z)$, $Z_m(z)$ and $R_m(z)$ are monic Schur polynomials with degrees $m^*$ and $n^*$, respectively. In addition, $y_m(k)$ and $r(k)$ are the reference model output and a bounded reference signal, respectively. There is only one assumption for reference model, which is:

A4) $R_m(z)$ is an arbitrary Schur monic polynomial of relative degree $n^* = n - m > 0$.

The control action $u(k)$ is extracted from \( \Theta^T(k) \varphi(k) + r(k) = 0 \), where $\Theta(k)$ is the adaptive gains vector and $\varphi(k)$ is a vector formed by internal filters, plant output, reference signal and disturbance rejection terms. The $\varphi(k)$ consists in the following structure

$$\varphi^T(k) = [ \varphi_1^T(k) \varphi_2^T(k) y(k) u(k) V_s(k) V_c(k) ],$$

(5)

where $\varphi_1(k)$ and $\varphi_2(k)$ are reconstructive filters, $y(k)$ is plant output, $V_s(k)$ and $V_c(k)$ are phase and quadrature components of exogenous disturbance, respectively. The internal filters are

$$\varphi_1(k + 1) = (I + FT_s)\varphi_1(k) + qT_su(k),$$
$$\varphi_2(k + 1) = (I + FT_s)\varphi_2(k) + qT_sv(k),$$

(6)

where $I$ is an identity matrix of dimensions $n \times n$ and $(F, q)$ is a controllable pair with a stable matrix $F$ and a vector of controllable parameters $q$, with dimensions $n - 1 \times n - 1$ and $n - 1$, respectively (IOANNOU; TSAKALIS, 1986). In addition, $T_s$ is the sampling time.
A Least Square algorithm (IOANNOU; SUN, 2012) was utilized for gains adaptation of controller:

$$\theta(k+1) = \theta(k) - T_s \sigma(k) P(k) \theta(k) - T_s \kappa P(k) \xi(k) \varepsilon(k) m^2(k),$$

(7)

where \(P(k)\) is the covariance matrix, \(\kappa\) is a positive parameter that accelerates parametric convergence pondering the augmented error \(\varepsilon\), which is

$$\varepsilon(k) = y(k) + \theta^T(k) \zeta(k),$$

(8)

where \(\zeta(k)\) is the \(\omega(k)\) filtered by reference model,

$$\zeta = W_m(z) \omega.$$  

(9)

The parametric convergence is defined by covariance matrix \(P(k)\), which is computed as

$$P(k+1) = P(k) - T_s P(k) \zeta(k) \xi^T(k) P(k) + T_s \beta t,$$

(10)

where \(t\) is a matrix of ones and the term \(T_s \beta t\) is a modification on LS algorithm to prevent \(P\) to stagnate in zero. If it occurs, parameters are no longer adapted and the tracking error can be increased to an unacceptable level.

Furthermore, \(\sigma\)-modification was used to improve robustness into adaptive controller. It is a projection method that limits parameters increasing by their norm,

$$\sigma(k) = \begin{cases} 0 & \text{if } \|\theta(k)\| < M_0 \\ \sigma_0 \left( \frac{\|\theta(k)\|}{M_0} - 1 \right) & \text{if } M_0 \leq \|\theta(k)\| < 2M_0, \\ \sigma_0 & \text{if } \|\theta(k)\| \geq 2M_0 \end{cases}$$

(11)

where \(M_0 > \|\theta^*\|\) is the upper limit of \(\theta(k)\) norm, securely oversized due to lack of knowledge of \(\|\theta(k)^*\|\) and \(\sigma_0\) is the maximum value of the modification function (EVALD; TAMBARA; GRÜNDLING, 2020b).

Moreover, a majorant signal \(m^2(k)\), similar to a normalizer, was also implemented to ensure robustness to the adaptive controller. Here, it was designed as shown in (EVALD; TAMBARA; GRÜNDLING, 2020a),

$$m^2(k) = 1 + \xi^T(k) \xi(k).$$

(12)

The block diagram of presented control method is shown in Figure 2, where \(e_1(k)\) is the tracking error, calculated as the difference between plant and reference model outputs, \(e_1(k) = y(k) - y_m(k)\).
4 Simulation Results

Simulations of the closed-loop system were carried out in the Octave 6.1, and they include converter switching dynamics, governed by SVM (PINHEIRO et al., 2005), to synthesis the control action. Also, the controller was synchronized with the grid voltage by a Kalman Filter algorithm (CARDOSO et al., 2008). Furthermore, grid voltages, which were estimated with Kalman filter, are also used to identify phase and quadrature of grid disturbance, with the aim of rejecting it, and to generate a reference signal. It is highlighted that, for some cycles, while initial synchronization occurred, the converter was maintained inhibited.

The grid frequency, line voltage range and DC bus voltage were set to 60 Hz, 110 V and 250 V, respectively. Besides, the converter’s switching frequency and the controller’s sampling frequency were both set to 5 kHz. The parameters of grid and LCL filter are shown in the Table 1, which is identical to the experimental setup of (EVALD; TAMBARA; GRÜNDLING, 2020b).

The reference model was chosen to have unit gain in steady state regime and presents fast dynamics. It is identical for both coordinates, given as follows,

$$ W_m(z) = \frac{Z_m(z)}{R_m(z)} $$

Due to the adaptive nature of the controller, the controller parameters can be chosen empirically over a large range, which will convergence to a set of parameters that minimizes the tracking error in steady state. The LS parameters were determined through a set of simulations, aiming for fast tracking and low overshoot. The resulting values are: $P(0) = 100I$,
\[\beta = 50 \text{ and } \kappa = 15.\] These parameters determine the convergence rate: as higher they are, the faster will be the parametric convergence. However, if they are chosen with excessively high values, the algorithm can impose an oscillatory behavior to \(\theta\) gains, and, consequently, they cannot converge. In the future steps of this study, the design constraints will be determined through Lyapunov’s stability criterion. Besides, the parameters of \(\sigma\)-modification were chosen as \(\sigma_0 = 0.1\) and \(M_0 = 10\), which can be oversized due to unknown norm of \(\theta\) (EVALD; TAMBARA; GRÜNDLING, 2020b). Moreover, the initial value of majorant signal was chosen as one, \(m^2(0) = 1\), to avoid division by zero on \(\theta(1)\) computation, once it will be continuously re-calculated based on \(\zeta\) dynamics. Finally, the pair \((F, q)\) was set to \(F = 1000I\) and \(q = [1000\ 0]\) to impose a soft dynamics on internal filters \(\omega\).

Moreover, all parameters of \(\zeta\) and \(\omega\) were initialized as zero. In addition, to avoid excessive overshoot in the initial transient regime, a previous simulation was performed, considering the designed controller parameters, using a reference sinusoidal signal with an amplitude of 10 A and a frequency of 60 Hz, without grid impedance variation. The final gain values achieved in this simulation were taken to initialize \(\theta(0)\) vector of presented simulation. These values are

\[
\theta_{\alpha}(0) = \begin{bmatrix}
-1.85698976 \\
0 \\
-0.71954155 \\
0 \\
-1.1173636 \\
-1.9491602 \\
3.8845067 \\
-0.36709696
\end{bmatrix}, \quad \theta_{\beta}(0) = \begin{bmatrix}
-0.71336466 \\
0 \\
-0.35032609 \\
0 \\
-0.88017768 \\
-1.2983845 \\
1.8041753 \\
-0.3386625
\end{bmatrix}.
\]

The initial reference current has an amplitude equal to 15 A. At 0.1 s, this amplitude is increased to 25 A. In addition, at 0.15 s, a parametric variation on grid impedance is imposed, by adding 0.4 mH with 50 mΩ only on phase \(a\), unbalancing more the grid. Figure 3 shows...
grid-side currents in three-phase coordinates, followed by currents tracking in \( \alpha \beta \) coordinates on Figure 4.

![Figure 3 – Grid-side currents in abc coordinates](image)

![Figure 4 – Grid-side currents in \( \alpha \beta \) coordinates](image)

As can be observed on Figure 3, the grid-injected currents presented a well-controlled behavior. The reference tracking occurred very quickly, as can be better seen on \( \alpha \beta \) coordinates, shown on Figure 4, with short transient response, which was around two grid cycles. It can be noted that currents were very close to the reference model outputs, even when parametric variation was imposed on the grid impedance. Moreover, the controller dealt properly with exogenous disturbances from the electrical grid. The tracking errors are shown in Figure 5. Note that tracking errors are greater on initial transient regime, due to grid uncertainties, which forced the gains to readapt, as well as at reference change instant, because it imposed a great active power output increase. The gains in adaptation \( \theta(k) \) are shown in Figures 6 and 7, for \( \alpha \) and \( \beta \) coordinates, respectively.

Figure 5 – Tracking errors in $\alpha\beta$ coordinates
Fonte: The author.

Figure 6 – Gains in $\alpha$
Fonte: The author.

Figure 7 – Gains in $\beta$
Fonte: The author.
As expected, the gains presented more action on initial transient regime and at reference change instant, converging on steady state regime. The covariance matrices convergence are presented in Figures 8 and 9, for $\alpha$ and $\beta$ coordinates, respectively.

As can be noted, all parameters of gain vector and covariance matrix converged on steady state and remained with limited values on transient regimes, which means that majorant signal is robust enough to ensure boundedness of all closed-loop system signals. Finally, in Figure 10, the control actions are presented. Note that for grid disturbance rejection and properly reference tracking, no excessive efforts were required by the controller, even with unbalanced grid conditions, being feasible for experimental implementation.
5 Conclusion

In this work, it was presented a discrete-time direct Output Feedback-based LS-RMRAC for grid-injected currents control of a static 3-wire three-phase converter with LCL filter, under unbalanced grid voltage condition. The proposed method dealt properly with grid disturbances, parametric variations of grid impedance, even on unbalanced grid conditions. The proposed controller presented fast current tracking, with low initial overshoot and small tracking error on steady state, requiring feasible voltage to synthesize control action, considering many implementation aspects on simulation, such as: digital implementation delay, converter switching, grid uncertainties and grid voltage synchronization. Therefore, results indicate that it can be securely applied to experimental power plants. In a future work, controller design constraints will be investigated through Lyapunov’s stability criterion.

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