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Simplified Model of a Grid-Connection Interface Based on Power Electronic Converter for Grid Studies in Dynamic Regime

Modelo simplificado de una interfaz de conexión a la red basada en un convertidor electrónico de potencia para estudios de red en régimen dinámico

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Abstract

The paradigm change experienced by worldwide power systems has led to a massive participation of new energy agents: generation, storage, and consumption. In most cases, these agents are equipped with power electronic converters (PEC) to incorporate their energy to the grid. This reality has motivated the development of highly sophisticated and detailed PEC analytical models that accurately represent their dynamics and enable to study their impact on the grid in a simulation environment. However, when it comes to studying large-scale power systems or with all their components disaggregated, the huge computational burden required to simulate a detailed model could make these studies unfeasible.

Resumen

El cambio de paradigma experimentado por los sistemas eléctricos a nivel mundial ha propiciado una participación masiva de nuevos agentes energéticos: generación, almacenamiento y consumo. En la mayoría de los casos, estos agentes están dotados de convertidores electrónicos de potencia (CEP) para verter su energía a la red. Esta realidad ha impulsado el desarrollo de modelos analíticos muy sofisticados y detallados de CEP para estudiar el impacto de su interacción con la red en un entorno de simulación. No obstante, cuando se trata de estudiar redes de gran dimensión o con sus componentes desagregados, la enorme carga computacional requerida para simular un modelo detallado podría suponer una limitante para la realización de tales estudios.

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This paper proposes the design of a simplified model of a grid-connection interface based on PEC for power system analysis using MATLAB/Simulink®. The model is designed to represent, with reasonable numerical accuracy, the dynamic behavior of certain electrical variables of interest that would produce a detailed model and, at the same time, to achieve a noticeable reduction in the computation time. A comparative analysis of the numerical results, the dynamics generated, and the convergence time achieved by the two models enable to validate the proposal. These milestones make it possible to fulfill the objectives of this research.

Keywords: Computer Simulation, Energy Conversion, Power Electronic Converter, Power Systems, Pulse Width Modulation

En este artículo se propone el diseño de un modelo simplificado de una interfaz de conexión a la red basada en CEP, útil para estudios de red mediante MATLAB/Simulink®. El modelo está concebido para representar, con una precisión numérica razonable, el comportamiento dinámico que tendrían ciertas variables eléctricas de interés de un modelo detallado y, al mismo tiempo, para conseguir una reducción significativa del tiempo de cómputo. Un análisis comparativo de los resultados numéricos, las dinámicas generadas y el tiempo de convergencia de los dos modelos permite validar la propuesta. Estos hitos conseguidos permiten cumplimentar los objetivos planteados en esta investigación.

Palabras clave: convertidor electrónico de potencia, conversión de energía, modulación por ancho de pulso, simulación por computadora, sistemas eléctricos de potencia

1. Introduction

In recent decades, electrical power systems have experienced a paradigm change that has forced them to go from a predominantly centralized generation model to a more distributed generation model and even to an intelligent electricity grid model, together with the inclusion of new energy generation, storage and consumption agents [1,2]. In the framework of this transition, renewable electric generators, electric vehicles, energy storage systems, among others, are being increasingly integrated, and their grid-connection interface is based on power electronic converters (Figure 1).

This is because the electricity generated/consumed by these agents is incompatible with the grid in terms of type of energy (direct current or alternating current), amplitude and frequency of the voltage, etc. The need to employ electronic converters to incorporate to the grid the energy coming from renewable generators (for instance, wind or photovoltaic), complies with criteria of obtaining the maximum efficiency in converting the primary energy resource into electrical energy [3, 4]. In the case of charge stations of electric vehicles, the energy supplied to the batteries is handled by power electronic converters with the purpose of guaranteeing the efficiency of the process and safeguarding the useful life of such batteries [5].

A similar situation applies to battery energy storage systems, in which the energy flow may go from the battery to the grid or vice versa according to the need of the grid of having or storing energy [6]. The power electronic converters have a topology that enable the bidirectional flow of active and reactive power depending on the set points preestablished in the control systems that govern the firing logic of the semiconductors that constitute them. Therefore, from the perspective of the grid, these interfaces behave as current controlled sources [7].

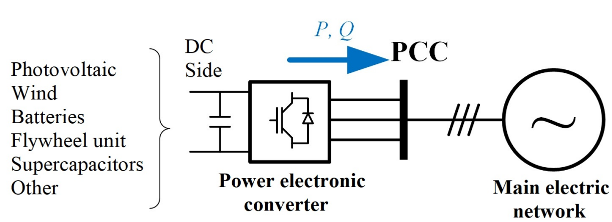


Figure 1. Power electronic converter connected to the grid

In the operation of a power electric system in dynamic regime, a reduced participation of renewable generators with grid-connection interface based on power electronic converters does not involve a severe stability problem (of frequency and voltage), since this task is successfully carried out by conventional synchronous generation. However, as this integration is massified (substituting synchronous generation), the grid starts to show a decrease in its inertial characteristics and, consequently, the operating conventional electric generation may result insufficient to guarantee stability of the system in case that a fault or contingency occurs [8].

This situation is of great concern in weak and isolated electric systems, in which the participation quota of renewable generation in the energy mix is comparable or exceeds conventional generation, as demonstrated by studies published in [9–11]. However, many of the solutions proposed in the literature to mitigate the aforementioned problems are precisely based on the use of more electronic converters, usually associated to energy storage systems (batteries, flywheel units, supercapacitors, among others).

This initial presentation intends to show the relevance claimed by power electronic converters in the operation of an electric system, which has motivated the development of very detailed and complete models devised to emulate its dynamic behavior and interaction with the grid, and to be used in studies based on computer simulations [12, 13]. However, when the object of a study is the dynamic analysis of large-scale power systems or of electric systems with all their components disaggregated, the huge computational load required to simulate detailed models of converters in a time range from few seconds up to a couple of minutes (time in which physical phenomena related with the frequency/voltage stability in the grid show up) might limit, to a large extent, conducting this type of studies.

This situation has motivated the search for methodological alternatives that enable modeling power electronic converters in a less complex way, without affecting its numerical accuracy with respect to results that might be provided by a traditional detailed model. For example, recent works published in [14–17] present effective techniques to achieve a significant simplification of the control logic of power electronic converters, all them based on the predictive control of finite states based on the FCS-MPC model.

The results reported in these contributions show that the control of converters through FCS-MPC enables reducing the execution time of control loops, compared to that associated to the implementation of classical linear controllers, without a degradation in its performance. However, this benefit brings along the need to perform a larger number of calculations to fulfill control objectives. To mitigate this situation, these papers propose different designs of matrix converters oriented to reduce the number of sectors necessary for the vector decomposition of the three-phase voltage in the point of common coupling, either by means of a simplification of the formulation used [15–17] or through the use of search tables that speed up the calculation process [14].

A common feature of these scientific contributions is that the proposed simplifications focus on optimizing the control logic of the converter but maintaining a detailed representation of the three-phase inverter (bridge of 6 or 9 power transistors). In contrast, [18] states a simplification idea focused on the three-phase inverter, represented by means of a bridge of six controlled current sources, modulated through SPWM, whose computational gains are latent as evidenced by the reported results. They also envision that the goodnesses obtained by simplifying the analytic representation of the three-phase inverter are depleted, to a certain extent, when using a pulse-width modulation technique for controlling the controlled current sources, which demands an important computational effort for its implementation. It is here where the research gap that gave rise to the statement of the present proposal was identified.

With the purpose of achieving a larger degree of simplification, and at the same time maintaining a compromise between simplicity and accuracy, it is proposed the development of a simplified model of a grid-connection interface based on power electronic converters to be used for studies of grids in dynamic regime in the MATLAB/Simulink® simulation environment. The three-phase inverter is represented by three controlled current sources governed by a pair of linear controllers in the $d-q$ coordinates designed for this research. For this purpose, it is taken as reference the theoretical basis of the operation principle of the detailed model of a complete power electronic converter and its implementation in the simulation program

2. Materials and methods

The research developed in this work is experimental, since the experiments, conducted in a computer simulation environment, are carried out under controlled conditions [19].

In the first instance, the theoretical basis and the implementation of a detailed model of a power electronic converter (PEC) are presented. Then, it is stated the development of the simplified model devised to emulate the dynamical behavior that would have the detailed model, from the point of view of the grid, within the time horizon of interest delimited in this research. At the same time, it is sought to achieve a significant reduction of the computational effort required to represent the dynamics of particular electrical variables handled by the PEC in the simulation. These are the main objectives of the research.

2.1. Detailed representation of a power electronic converter

Figure 2 shows the typical configuration of a PEC connected to the grid. In the illustration, it is possible to distinguish two subsystems: the three-phase inverter and its power controller PQ. The inverter, constituted by a bridge of power semiconductors (SCR, MOSFET, IGBT, or others, according to the application), has the function of converting the energy coming from a direct current (DC) system into alternating current (AC) energy for its further incorporation in the three-phase grid, or vice versa. Based on the switches that are closed at each time instant, the bridge will be constructing a three-phase voltage signal at its terminals whose fundamental frequency will be inherited from the voltage established by the grid at the point of common coupling (PCC), and whose amplitude and phase will be defined by the current that is required to be injected to achieve a predetermined value of active and reactive power at the PCC by the converter.

The firing sequence applied to each of the six semiconductors of the inverter is implemented using pulse width modulation techniques, whose principle is described in section 2.1.1., whereas the tasks of controlling the injected active and reactive power are carried out by means of a PQ control scheme similar to the one shown in the lower subsystem in Figure 2, whose criteria are explained with more detail in section 2.1.2. In addition, it should be indicated that, with the purpose of reducing the harmonic content of the current signal injected by the PEC at the PCC, this topology is frequently used together with a first-order three-phase passive filter as seen in the figure.

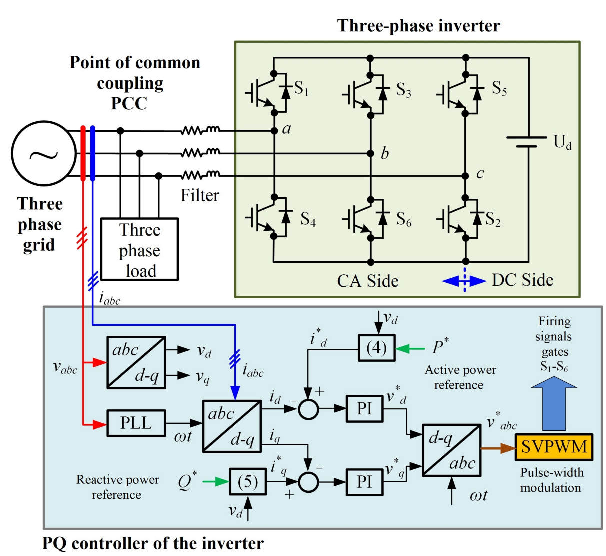


Figure 2. Typical configuration of a three-phase PEC connected to the grid

2.1.1. Space vectors pulse-width modulation (SVPWM)

For generating the firing signals of the gates of the transistors that constitute the PEC topology, there are currently available many techniques with great applicability and high degree of maturity, such as: pulse-width modulation (PWM), selective harmonic eliminated pulse width modulation (SHE-PWM), sinusoidal pulse width modulation (SPWM) and space vectors pulse-width modulation (SVPWM) [20–22]. With the recent advances in the industry of semiconductors, microprocessors and in digital signal processing, the space vectors pulse-width modulation techniques are widely used in the PEC for applications of electric power generation due to their greater flexibility in the control, lower harmonic content and better dynamic performance [22, 23].

In general, the SVPWM is a digital modulation technique in which a sampled reference vector is synthetized through an appropriate number of state vectors switched at particular time instants. Both the reference vector and the vector of switched states are represented in a complex plane through a transformation from an abc three-phase reference framework to a reference framework in $\alpha-\beta$ coordinates. In order to provide the reader a first approximation to the method, consider the three-phase inverter shown in Figure 2. This topology offers eight switching states, which are arranged according to the a, b, c sequence. Starting from the premise that in each of the three branches of the bridge of transistors only one of them can be active (or in conduction), it is defined as switching state 1 the case when the upper transistor in the branch is active, and 0 when it is active the lower transistor in the branch.

If the voltage at the DC side of the inverter is defined as Ud, such inverter is capable of offering at its terminals the volage values (phase voltages $\boldsymbol{V_A}$, $\boldsymbol{V_B}$ and $\boldsymbol{V_C}$, and line voltages $\boldsymbol{V_{AB}}$, $\boldsymbol{V_{BC}}$, $\boldsymbol{V_{CA}}$) shown in Table 1. Now, the SVPWM technique is defined by the sequence in which each of the eight switching combinations is selected and the time for which each of them should remain active. Figure 3 gives a graphical idea of the mechanics for constructing the voltage vector $\boldsymbol{V_n}$ at the inverter terminals, on the stationary complex plane $\alpha-\beta$. This vector is decomposed in eight switching states, namely $\boldsymbol{V_0}$ to $\boldsymbol{V_7}$, of which $\boldsymbol{V_1}$-$\boldsymbol{V_6}$ are active vectors that constitute a regular hexagon (six sectors), and $\boldsymbol{V_0}$ and $\boldsymbol{V_7}$ are null vectors that lie at the center of the hexagon. A detailed description of the theoretical framework of this modulation technique, calculation of switching times for each of the sectors and implementation criteria may be found in [12, 13, 24].

Table 1. Switching states of the three-phase inverter

State			Voltages at the inverter terminals					
a	b	c	V_A	V_B	V_C	V_{AB}	V_{BC}	V_{CA}
0	0	0	0	0	0	0	0	0
0	0	1	-U_d/3	-U_d/3	2U_d/3	0	-U_d	U_d
0	1	0	-U_d/3	2U_d/3	-U_d/3	-U_d	U_d	0
0	1	1	-2U_d/3	U_d/3	U_d/3	-U_d	0	U_d
1	0	0	2U_d/3	-U_d/3	-U_d/3	U_d	0	-U_d
1	0	1	U_d/3	-2U_d/3	U_d/3	U_d	-U_d	0
1	1	0	U_d/3	U_d/3	-2U_d/3	0	U_d	-U_d
1	1	1	0	0	0	0	0	0

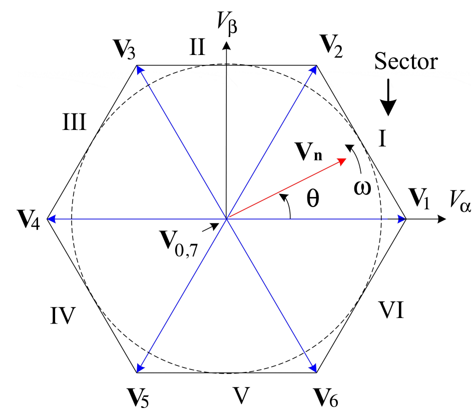


Figure 3. SVPWM modulation

2.1.2. Control of PQ power

For most industrial applications of PECs, the control of active and reactive power is carried out through the transformation of the three-phase voltage and current vectors expressed as components of a rotating coordinate system, where the vector of each variable is decomposed into vectors in the direct and quadrature $(d-q)$ axes [25]. From the theory of electrical power systems, Park transformation is the operator that enables transforming the abc representation of the three-phase electrical variables to a reference framework in the $d-q$ coordinates, as indicated in (1). In this equation, expressed for the current, $\boldsymbol{i_d}$, $\boldsymbol{i_q}$ and $\boldsymbol{i_0}$ correspond to the components in the direct, quadrature and homopolar $(dq0)$ axes, respectively, of the $\boldsymbol{i_a}$, $\boldsymbol{i_b}$ and $\boldsymbol{i_c}$ three-phase currents; ω is the angular frequency of the grid, which is the angular speed at which the d-q coordinate system rotates. Figure 4 shows an example in which the current vector $\boldsymbol{I}$ is decomposed into the $\boldsymbol{I_d}$ and $\boldsymbol{I_q}$ components. A similar reasoning may be applied to the voltage.

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \underbrace{\begin{bmatrix} cos\ \omega t & cos\ (\omega t - \frac{2\pi}{3}) & cos\ (\omega t + \frac{2\pi}{3}) \\ -sen\ \omega t & -sen\ (\omega t - \frac{2\pi}{3}) & -sen\ (\omega t + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}}_{Park\ transform} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

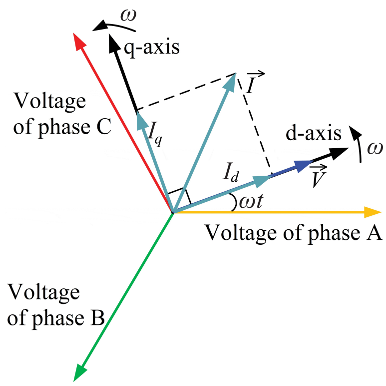


Figure 4. $d-q$ coordinate system

It has been demonstrated in the literature that the instantaneous powers in a three-phase system, may be calculated through the computation of the instantaneous voltage and current variables expressed in $d-q$ coordinates, as follows [26]:

$$P = \frac{3}{2}\left(v_d i_d + v_q i_q\right) \tag{2}$$

$$Q = \frac{3}{2}\left(-v_d i_q + v_q i_d\right) \tag{3}$$

Where:

v_d and i_d: instantaneous voltage and current in the direct axis.

v_q and i_q: instantaneous voltage and current in the quadrature axis

For analytical convenience, in this work it will be forced that the direct axis of the d-q coordinate system is aligned with the phase voltage vector, such that it is achieved that $v_q = 0$ and moreover, that $v_d = |\mathbf{V}| = V$. With this arrangement, the instantaneous powers are defined as follows:

$$P = \frac{3}{2} V i_d \tag{4}$$

$$Q = -\frac{3}{2} V i_q \tag{5}$$

This last pair of expressions shows the advantages of using the d-q coordinates for controlling the power injected to the grid by the PEC, since regulation of active power will only depend on the manipulation of variable i_d, whereas regulation of reactive power will depend on i_q. This implies that the control of power P may be carried out decoupled from the set-points applied to the control of power Q, thus requiring for this purpose the design of a single controller for each variable. The lower box in Figure 2 shows an implementation example of the PQ controller for the three-phase inverter under study.

2.2. Implementation of the detailed model of the power electronic converter in MATLAB/Simulink®.

Based on the above, this section presents the implementation of the detailed model of a power electronic converter in the MATLAB/Simulink® simulation environment. The grid illustrated in Figure 2 is defined as test bench, whose implementation in the simulator is shown in Figure 5.

Since the scientific interest of this work is focused on studying the interaction of the power electronic converter with the grid; an ideal voltage source will be connected at the DC side of the inverter, which may represent the primary energy resource from different agents such as: wind or photovoltaic generation, inertia flywheels, supercapacitors, battery banks, etc.

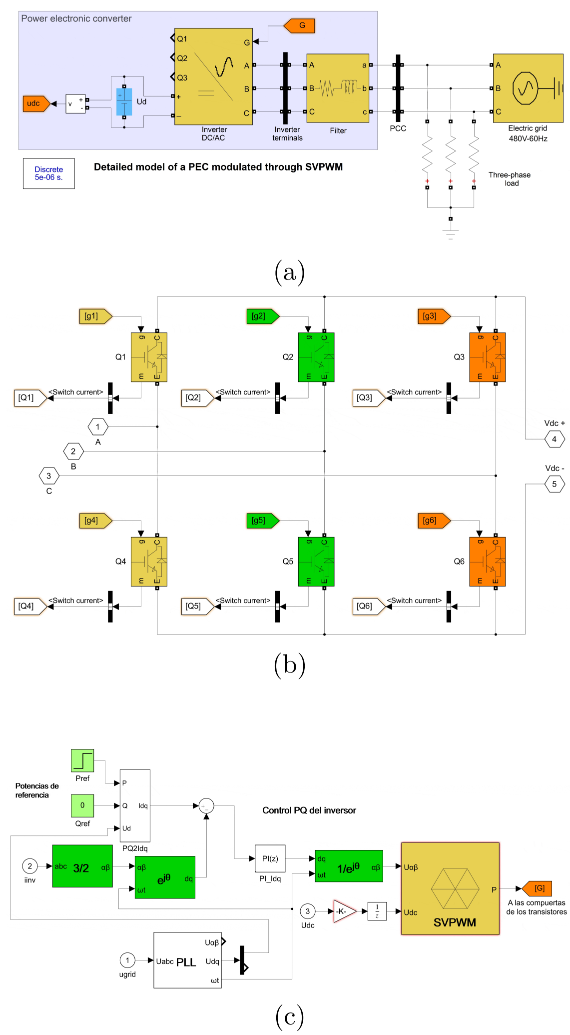
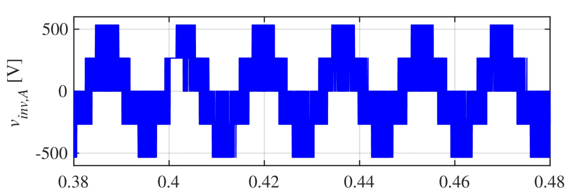


Figure 5. Implementation of the PEC in MATLAB/Simulink® (detailed model): a) test electric system; b) inverter configuration and; c) PQ controller and SVPWM modulator

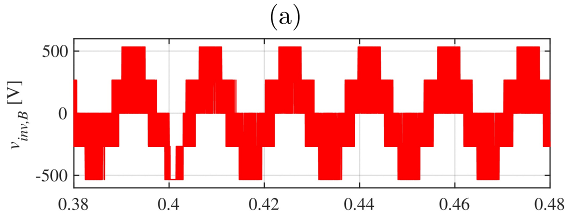
The values assigned to the parameters of the different elements that constitute the test system are provided in the Appendix. For more details about the implementation of the converter in the simulator, it is recommended to check [13].

In order to evaluate the performance of the detailed model of the power electronic converter in time domain in the simulation environment, a set-point is established for the active power that starts at a constant value of 10 kW, and changes to 20 kW after 0.4 s of simulation. In addition, a zero set-point has been set for the reactive power during the time horizon of the simulation, with the purpose of verifying the decoupled PQ control offered by the control philosophy through d-q coordinates. The following figures show the results obtained in the simulation.

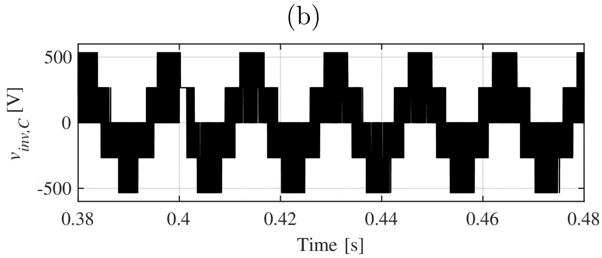
Figure 6 illustrates the phase-neutral voltage signal constructed by the three-phase inverter through the application of SVPWM modulation and measured at the inverter terminals (before the filtering stage). As it is seen in these plots, this voltage oscillates at the grid fundamental frequency (60 Hz) and presents a high-frequency component (20 KHz) inherited from the carrier employed for the pulse-width modulation, which will be attenuated by the series R-L filter.



(a)



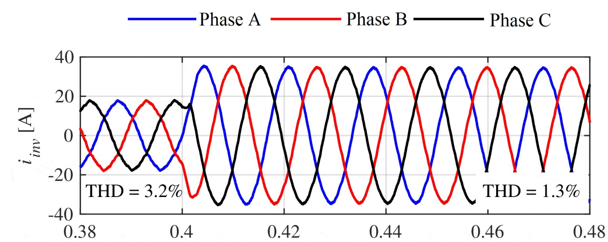
(b)



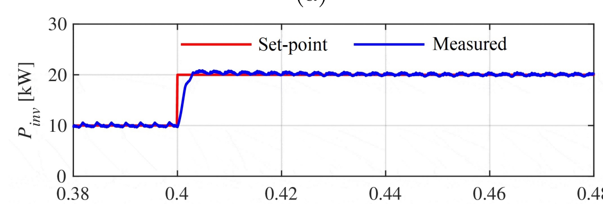
(c)

Figure 6. Three-phase generated at the inverter terminals

Figure 7(a) shows the wave shape of the current injected by the PEC at the PCC, which has been constructed by the PQ controller of the inverter to achieve the set-points established for active and reactive powers. The time domain dynamics shows the correct performance of the inverter and, moreover, the effectiveness of the filtering task (the values of total harmonic distortion (THD) are shown in the same figure). Based on the voltage and current measurements at the terminals of the PEC, the active and reactive powers injected at the PCC have been also plotted (Figures 7b and 7c, respectively). Note in Figure 7b that the PEC correctly tracks the active power set-point established in the PQ control system. Similarly, Figure 7c enables assessing the effectiveness of reactive power control, since this variable is maintained virtually at zero for the entire interval simulated. Moreover, this evidences one of the advantages offered by the PEC in its integration to the grid: the decoupled control of the P and Q powers.



(a)



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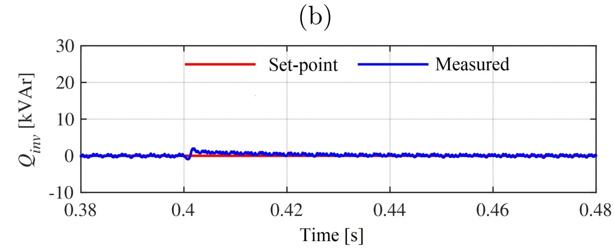


(c)

Figure 7. Electric variables measured at the output of the PEC: a) current; b) active power and; c) reactive powera

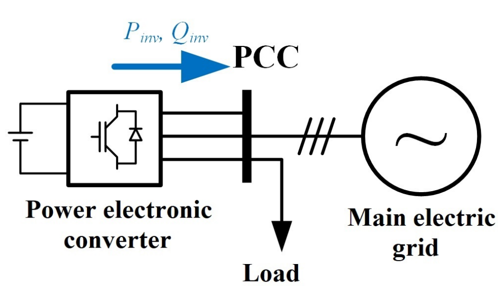
For the scientific interest of this study, focused in those phenomena that occur in the time horizon from milliseconds to few seconds in the operating dynamics of an electric power system (as it was justified in the introduction of this work), the set-points of both active and reactive powers are achieved by the PEC virtually instantaneously. This feature will be the premise for the simplified modeling addressed in the following subsection.

2.3. Design of the simplified model

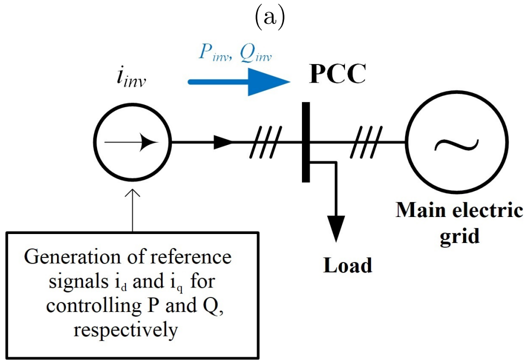
In studies of electric power systems in dynamic regime, whose objective is evaluating the impact of energy agents based on the grid-connection interface through power electronic converters, the use of a detailed model focused in the inner architecture of the PEC, such as the one presented in the previous section, may demand a high computational effort for representing its internal and external variables, which would make inviable many studies in simulation environments in the case of multimachine or large-scale grids. The objective of this work is to develop a simplified model that correctly emulates the dynamic behavior of a PEC seen from the grid at the point of common coupling (PCC), measured in terms of its electric variables. For this purpose, the operating principle, control criteria and simulation results described in section 2.1, will serve as starting point for the statement of the proposal.

2.3.1. Design criteria

First, consider the diagram shown in Figure 8a. This illustration is a synthetized representation of the electric system shown in Figure 2. According to the operating mode of the PEC, it will inject at the PCC some values of active and reactive power, P_{inv} and Q_{inv}, respectively, according to the preestablished set-points. Since the three-phase voltage at the PCC is imposed by the grid (in amplitude and frequency), the PEC will have to inject the three currents that will enable achieving the reference powers P^*_{inv} and Q^*_{inv}, as it is seen in the results illustrated in Figure 7. Therefore, from the point of view of the grid at the PCC, the PEC behaves as a controlled source of three-phase current (Figure 7a) whose amplitude and phase will depend, as it has been mentioned already, on the set-points of power.



(a)



(b)

Figure 8. Simplification criterion of the PEC model: a) general diagram; b) simplified representation

Based on the theory of the $d-q$ components (section 2.1.2), the injected three-phase currents are directly related with variables Pinv and Qinv, given its dependence on current components i_d and i_q, respectively (equations 4 and 5). Figure 8b illustrates the simplification criterion of the PEC model, representing it as a controlled current source, whose control scheme is developed hereafter.

Figure 9 shows the three-phase representation of the diagram of Figure 8b, in which the PEC is modeled by means of a controlled current source. This source will have to inject three-phase currents $i_{inv,A}$, $i_{inv,B}$ and $i_{inv,C}$ whose amplitude and phase will be defined according to the control criterion implemented and the applications assigned to the converter.

For generating the set-point signals of current, in this work it is proposed using the control scheme shown in Figure 10. According to this scheme, the three-phase signals applied to the controlled current source are generated based on the theory of the $d-q$ coordinate system, as explained in the following:

- For controlling the active power P^*_{inv}, a closed-loop PI controller is employed which generates at its output the signal i^*_d that will be in charge of regulating such power (equation 4). This signal is applied to a first-order delay function, introduced to represent the time it takes for the converter to reach the value of the control variable, i_d, from the time it is specified at its input, i^*_d.
- A similar control scheme is proposed for regulating the reactive power Q^*_{inv}, whose regulation is carried out analogously to the scheme described previously, but in this case manipulating variable i_q (equation 5).

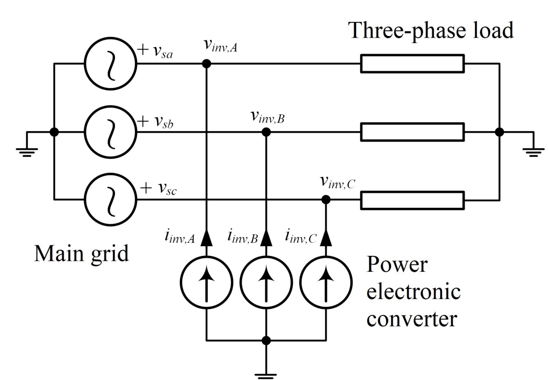


Figure 9. Proposed simplification of the PEC

Once signals i_d and i_q have been generated, they have to be transformed to an *abc* three-phase reference framework before being applied to the controlled source that represents the dynamics of the PEC. In order to carry out this transformation, the phase of the voltage at the PCC is measured in real time through a phase lock loop (PLL), to further evaluate Park transformation by means of (1). At last, to feedback the PI controllers in each of the control loops, it is measured the instantaneous values of the active and reactive power injected by the controlled current sources at the PCC.

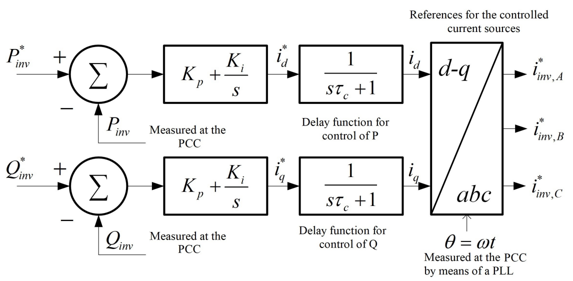


Figure 10. Proposed simplification for the PQ controller

2.3.2. Implementation of the proposal in MATLAB/Simulink®

Figure 11 shows the implementation of the PEC simplified model in the simulator on the same test bench used in section 2.1.3. It is noted the notorious simplification regarding complexity and number of elements necessary to represent the integration of the PEC to the grid, compared to the model of Figure 5.

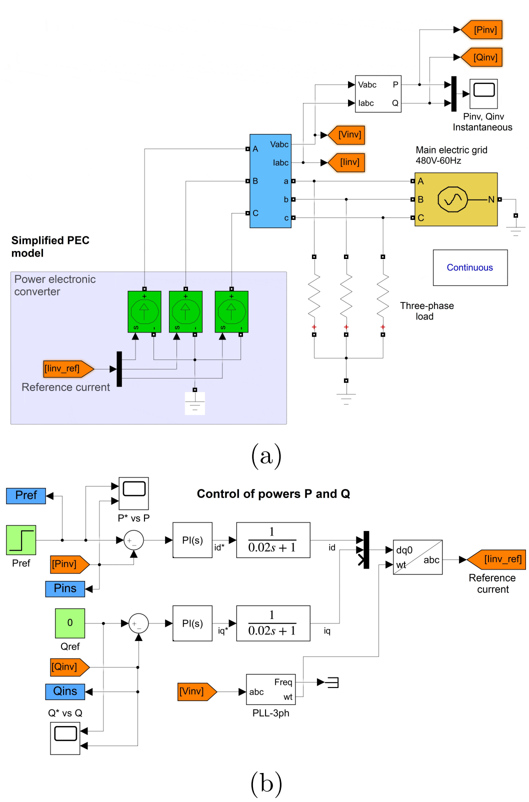


Figure 11. Implementation scheme of the simplified model: a) test electric system; b) PQ controller

In order to facilitate replicating the results of the simulation presented here, the reader is asked to review the values assigned to the different model parameters in the Appendix.

Hereafter, the proposed model is subject to the same operating conditions defined to simulate the detailed model: set-point signals for active and reactive power, time horizon for the simulation, main electric grid, load supplied, etc. The results illustrated in Figure 12a demonstrate that the three-phase current injected by the PEC is correctly generated, and that its amplitude and shape are very close to the ones obtained when simulating the detailed model (Figure 7a).

Figures 12b and 12c show the instantaneous active and reactive powers measured at the converter terminals. It is observed in these figures that the set-point values are successfully reached and faster than in the detailed model. Since the proposed simplified model is closer to the ideal operating conditions of a power electronic converter, the three-phase currents virtually lack of harmonic content, and moreover the instantaneous powers reach their target values almost immediately.

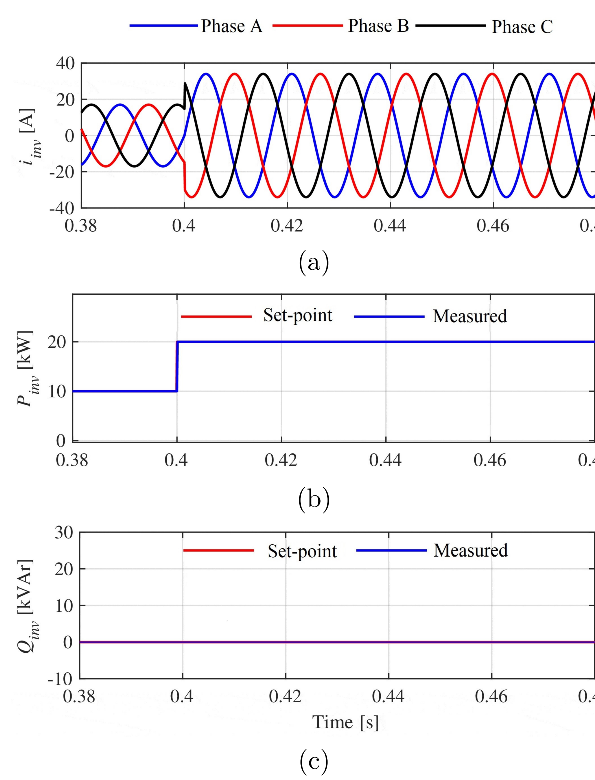


Figure 12. Electric variables measured at the output of the simplified model of the converter: a) current; b) active power and; c) reactive power

3. Results and discussion

This section presents a comparative analysis of the performance of the proposed simplified model (Figure 11), with respect to the detailed model taken as reference (Figure 5). For this purpose, the power set-point signals shown in Figure 13 were applied to both models, and they were subjected to the same operating conditions in the test bench designed in MATLAB/Simulink®.

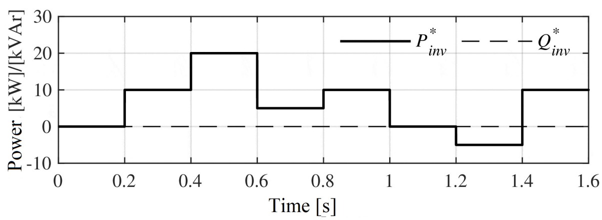


Figure 13. Power set-point signals applied to the converter

Figure 14 shows the results obtained in the simulation. It is observed in this figure the correct performance of both models in tracking the power set-points. This is an important conclusion, because these variables result from quantifying the three-phase voltage and current at the PEC terminals, and are most interesting ones in the dynamic study of electric power systems. The three-phase current achieved by the proposed model has virtually the same envelope of the corresponding current generated by the detailed model. The similarity between the dynamics of the variables of interest for both models in the short time horizon used in the plots, enables verifying the versatility of the proposed model and that the simplification in the representation of the main components of a PEC does not penalize significantly the numerical precision. Note that the resulting dynamics corresponds to the ideal behavior of a converter: much more immediate power transitions, absence of ripple in the injected powers and lack of harmonic content in the current signal. As the time horizon considered in the grid study of the proposed model enlarges, the impact of these limitations on the generated numerical results is smaller.

At last, regarding the computational benefits obtained with the implementation of the proposal, the simulation of the simplified model gives results in 4 % percent of the total computation time that it takes the detailed model to converge.

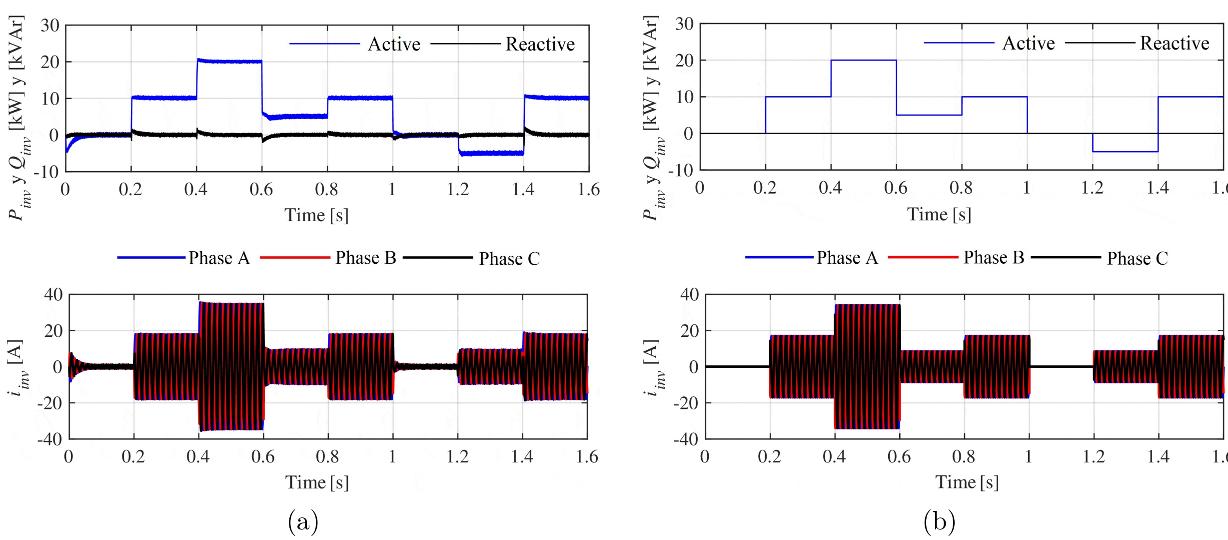


Figure 14. Simulation results: a) detailed model; b) simplified model

4. Conclusions

A simplified model of a grid-connection interface based on a power electronic converter for studies of grids in dynamic regime has been developed in this work. For this purpose, in the first instance an exhaustive review of the operating principle of a power electronic converter and its implementation in MATLAB/Simulink® was carried out.

Then, according to the theoretical basis described and analyzing the preliminary results of the simulation, a simplified model of the converter was developed such that it enables emulating a dynamic behavior similar to the one that would be obtained when simulating a detailed model.

The effort invested in the simplification and design tasks are justified after performing a comparative analysis of the dynamics generated by the two models, when being subject to the same operating conditions in the simulation environment. The numerical results and the dynamics exhibited by particular variables of interest are very close to each other, also achieving a reduction in the order of 96 % in the numerical computation time. These milestones enabled accomplishing the main objectives of this research work.

It is important to indicate that the proposed model gives numerical results that are closer to the ideal behavior of a power electronic converter, and hence there is an open possibility of incorporating certain improvements in future research works, such as:

- Add some harmonic content to the three-phase current signal injected, as a function of its amplitude.
- Perform a more exhaustive tuning process of the proportional and integral gains of the PQ controller.
- Apply modeling techniques, such as «hardware-in-the-loop», to achieve a more realistic characterization of the delay function assigned to the control loops of active and reactive power, among others.

Appendix

A. Electric grid parameters:
Three-phase source: $V_{ab(rms)} = 480$ V, f = 60 Hz
Three-phase load: $P_{LA} = P_{LB} = P_{LC} = 1{,}00$ kW.

B. Detailed model parameters:
SVPWM modulation: $f_{carrier} = 20$ kHz
PI controller: $K_P = 50$ y $K_I = 2500$
Series R-L filter: $R_f = 0.1\ \Omega$ y $L_f = 12{,}7$ mH
DC voltage: $U_d = 800$ V

C. Simplified model parameters:
P controller: $K_p = 5$ y $K_i = 50$
Q controller: $K_p = -5$ y $K_i = -50$
Delay function time constant: $\tau_C = 0{,}02$ s

D. Simulator parameters

	Detailed model	**Simplified model**
Solver	ode3 (Bogacki-Shampine)	ode23tb (stiff/TR-BDF2)
Step size for numeric calculation	5×10^{-6} s (fixed)	$0{,}5\times10^{-3}$ s (variable max.)

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