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Analysis and Control of Power Converters using co-Simulation

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RESUMEN

El presente artículo presenta el estudio de varios métodos de control para conversores de potencia. Dichos métodos serán implementados mediante co-simulación. En primer lugar, se analizará el rectificador monofásico, se obtendrá un modelo matemático y se lo resolverá numéricamente usando Matlab. Esto tendrá mucha utilidad para estudios futuros a cerca de la controlabilidad de los rectificadores. Posteriormente, se presentará una co-simulación de los sistemas de control propuestos para el rectificador monofásico y el trifásico. Finalmente, se estudiará también el inversor trifásico y se implementará un sistema de control usando modulación espacio vectorial a través de co-simulación.

Palabras clave: Conversores de potencia, modelos matemáticos, sistemas de control, modulación PWM, co-simulación.

ABSTRACT

This paper presents the study of several control methods for power converters. Those methods will be implemented with co-simulation. In first place, the single phase rectifier will be analyzed, a mathematical model will be obtained and will be solved numerically using Matlab. This will be useful in future studies about the controllability of rectifiers. Later, a co-simulation of control systems for a single and three-phase rectifier will be presented. Finally, the three-phase inverter will be also studied and a control system using space-vector modulation will be performed in co-simulation.

***Key words*: Power converters, mathematical models, control systems, PWM modulation, co-simulation.**

TABLA DE CONTENIDO

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***Abstract*—This paper presents the study of several control methods for power converters.Those methods will be implemented with co-simulation. In first place,the single phase rectifier will be analyzed, a mathematical model will be obtained and will be corroborated using Matlab. This will be useful in future studies about the controllability of rectifiers. Later, a co simulation of control systems for a single and three-phase rectifiers will be presented. Finally, the three-phase inverter will be also studied and a control system using space-vector modulation will be performed in co-simulation.**

I. INTRODUCTION

Power converters are highly important electronic systems because of their numerous applications. Although they have been studied for many years, they are currently gaining even more attention due to the progressive improvement of semiconductors in power switches, improvements that have made them obtain faster switching characteristics and less power dissipation. Thanks to that, some projects that were not possible before, such as solid-state transformers for smart grids, are now feasible [1].

The control of power converters can be done using both analog and digital techniques, however the digital techniques are the ones that have been studied more in the last years due to the nature of the controlled converters, which basically consist of switches that commute between states Of conduction and non-conduction, which is easily attached with the digital nature of zero and one [2].

The systems that will be discussed in this article will be studied through co-simulation, using two programs, Simulink on one side to implement control loops and modulation techniques, and PSpice will be used to build the circuits that will be the plants In the control systems. This will be achieved using a module called SLPS, which is a new product that has recently been released. It is important to emphasize that co-simulation provides a more real analysis of the system of interest than using a mathematical model, since it considers many other factors than just a transfer function.

Two principal types of power converters will be studied in this paper, the rectifier and the inverter. In section II, a mathematical model for the rectifier will be derived and its behavior across time discussed. A co-simulation of a voltage control system for the single phase rectifier will be implemented in section III. Also, in section III, a predictive control technique for three phase rectifiers will be explained and then verified in co-simulation. Finally, a current control technique based on space vector modulation for the three phase inverter will be presented, which will be also verified in co-simulation.

II. CONVERTER MODELING AND ANALYSIS

This section presents the development and analysis of single and three phase controllable and uncontrollable rectifier models. These models are explored within their most common application scenario where controllability conditions are examined in detail. The discussion begins the development and analysis of a single-phase full-bridge line-commuted rectifier.

A. Single-phase line commuted rectifier

Single-phase line commuted rectifiers are probably one of the most used converters. Their main purpose is to rectify the mains voltage. Load voltage is usually controlled using thyristors, which allow control on voltages below the mains peak value, by using voltage phase control. Disadvantages common of this configuration are usually due to the amount of harmonics in the load voltage and mains current. In particular, if the load is highly inductive, thyristor turn-off and voltage waveform are to be considered in detail [3]. In general, load voltage is required to be as steady as possible and this is usually attained by using a capacitor. This however has the detrimental effect of input current distortion which produces a low power factor. Figure (1) shows a simple diagram of the line-commuted rectifier.

The behavior of the line-commuted single phase rectifier with a capacitive filter on the output and a line inductor can be modeled by 4 differential equations which describe the mains current and the capacitor voltage.

The capacitor can be either under a charging condition or discharging condition, which depends on the inductor current. Whereas the inductor current can be either circulating or not. The current conditions are determined by the relation between the $v_{afe}(t)$ and the capacitor voltage.

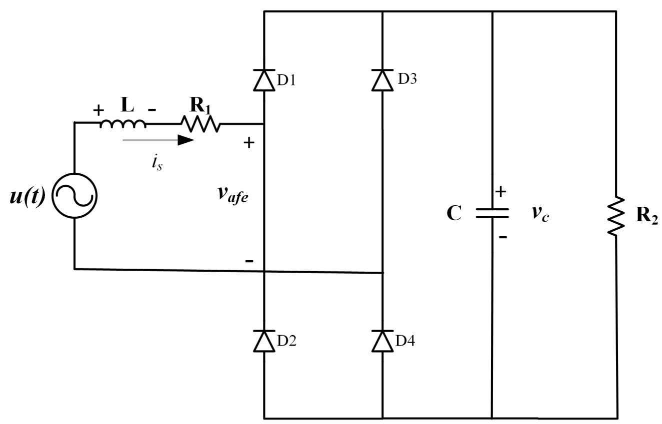


Fig. 1: Single-phase line commuted rectifier

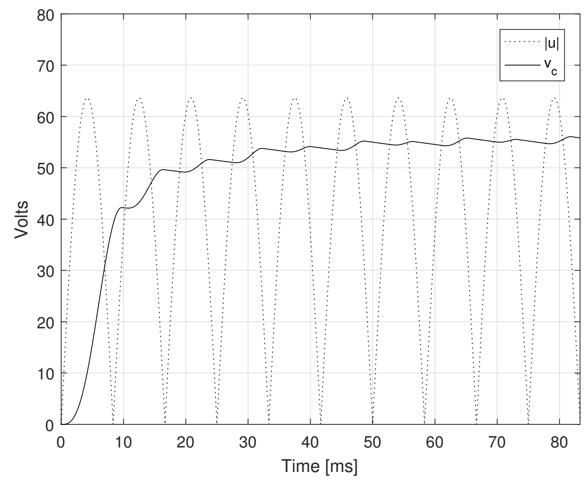


Fig. 2: Rectified mains voltage and capacitor voltage. $L = 6.6mH$, $C = 3mF$, $R_1 = 1\Omega$, $R_2 = 110\Omega$, $V_s = 45V$

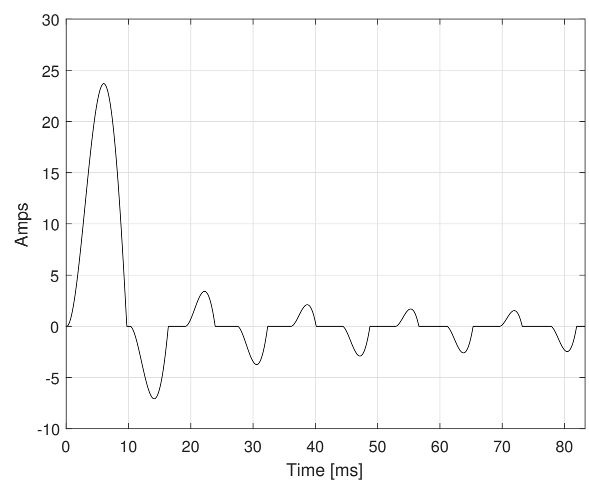


Fig. 3: Inductor current. $L = 6.6mH$, $C = 3mF$, $R_1 = 1\Omega$, $R_2 = 110\Omega$, $V_s = 45V$

Mathematically we can describe the circuit behavior with the following set of equations,
If $|i_s| > 0$

$$\frac{dv_c}{dt} = -\frac{v_c}{R_1 C} + \frac{|i_s|}{C} \quad (1)$$

$$v_{afe} = sgn(i_s)\,(v_c + v_{break}) \quad (2)$$

If $|i_s| = 0$

$$\frac{dv_c}{dt} = -\frac{v_c}{R_1 C} \quad (3)$$

$$v_{afe} = u \quad (4)$$

If $|v_{afe}| \geq v_c + v_{break}$

$$\frac{di_s}{dt} = \frac{u}{L} - sgn(i_s)\frac{v_c}{L} - \frac{R_2}{L}i_s + \frac{v_{break}}{L} \quad (5)$$

If $|v_{afe}| < v_c + v_{break}$

$$\frac{di_s}{dt} = -\lambda i_s \quad (6)$$

where, v_{break} is the total diode threshold voltage, and λ is a large enough positive number. Equation (6) has been introduced for numerical reasons. A theoretical model should consider $\frac{di_s}{dt} = 0$ instead.

Figures (2)-(4) show the output voltage $v_c(t)$, mains current $i_s(t)$ and bridge front-end $v_{afe}(t)$.

B. Single-phase regenerative rectifier

One the of the main problems in line-commuted rectifiers, besides that it is not possible to control load voltage is the high harmonic content of the input current. High harmonic content produces excessive losses in the supply. Harmonic content in the mains current can be eliminated by using active power factor correction. There exist many topologies for active power factor correction; however, the purpose of this paper is to study those in which it is possible to attain a reversal in the power flow or a regenerative behavior [4].

Such topologies build-up from the line-commuted rectifier by adding power semiconductors in parallel with the diodes as in Figure (5). This converter has several operation modes: line-commuted rectifier where T_1 through T_4 do not operate; and controlled converter.

As a controlled converter it is possible to resolve all of the disadvantages of the line commuted rectifier (power factor correction and output voltage control), achieve an output voltage higher than the mains and reverse power flow.

The analysis to understand how the converter works and therefore obtain an accurate dynamic model is divided into two regions: $v_c(t) \leq |u(t)|$ and $v_c(t) > |u(t)|$.

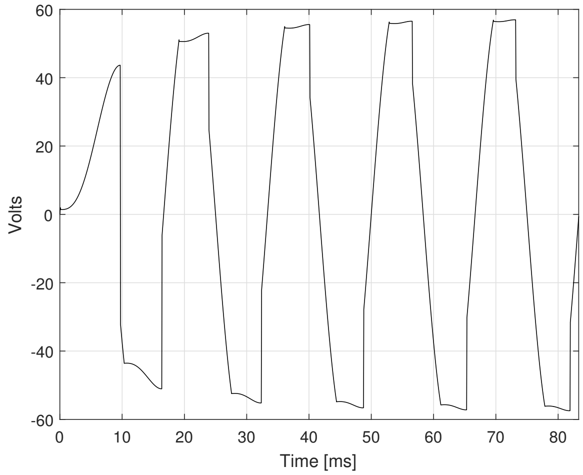


Fig. 4: Rectifier input voltage. $L = 6.6mH$, $C = 3mF$, $R_1 = 1\Omega$, $R_2 = 110\Omega$, $V_s = 45V$

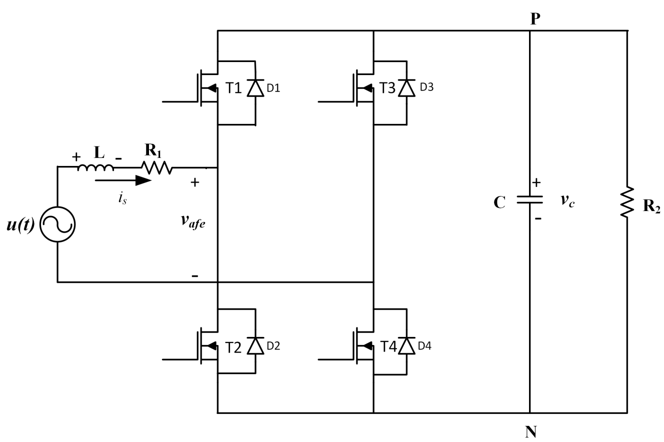


Fig. 5: Regenerative rectifier

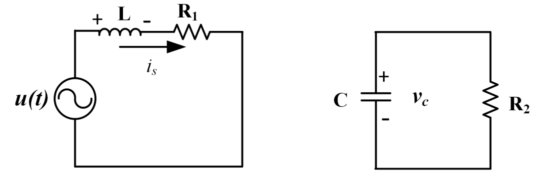
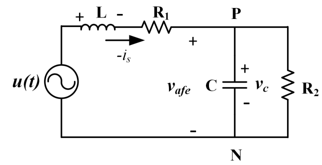
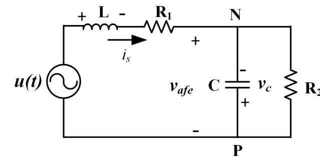


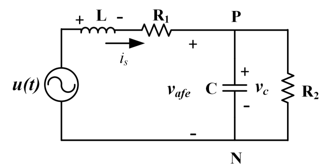
Fig. 6: Equivalent circuit for diodes and switches active simultaneously



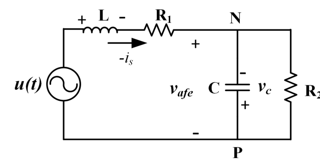
(a) $T1$ and $T4$ ON



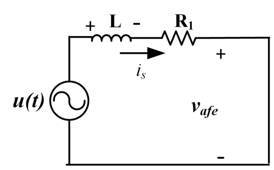
(b) $T2$ and $T3$ ON



(c) $D1$ and $D4$ ON



(d) $D2$ and $D3$ ON



(e) $T1$ and $T3$ or $T2$ and $T4$ ON

Fig. 7: Equivalent circuits for regenerative rectifier ($v_c(t) \leq |u(t)|$).

1) $v_c(t) \leq |u(t)|$: Under this condition it is possible that a set of diodes or switches are active at any time. Diodes and switches cannot be active at the same time. For example, consider D_1, D_4, T_2 and T_3 active. The mains current i_s will try to flow in both directions through the capacitor and effectively setting nodes P and N to the same voltage, thus no current will flow from the mains to the load through the converter [3]. The equivalent rectifier circuit for this condition is presented in Figure (6).

The main control objective is to shape the mains current as sinusoidal as possible and in phase with the voltage waveform. Adequate switch operation should be able to achieve such goal. As shown in Figures (7a) and (7b) when the switches are active the current will flow through the capacitor in the opposite direction of its polarity. When the switches are not active (during commutation) diodes will become active until the current through the inductor changes direction. Even though there is no direct control over the diodes they are necessary to provide an alternative path to current during switch commutation, otherwise the power semiconductors would be subjected to an excessively high dv/dt. When a set of diodes are forward biased, the voltage on the capacitor will be the voltage of the source plus the voltage of the inductor with the current flowing towards the load, therefore charging the capacitor at a higher voltage than the mains; as shown in Figures (7c) and (7d).

2) $|u(t)| \leq v_c(t)$: Under this condition, the diodes will not get biased unless there is an instantaneous change in the current flowing through the inductor which will produce a high voltage at its terminals. Since the switching frequency will be relatively high there will be small dead-times during which it could be possible that a set of diodes gets forward biased, specially if the line inductance is considerably high [4].

The equivalent circuit for the current have three possibilities depending on the state of the switches. Figure (7) shows these three possibilities.

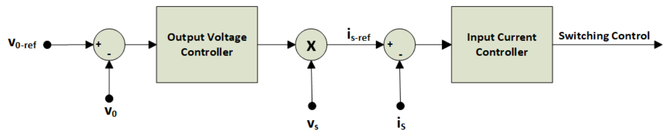


Fig. 8: Control scheme of the single-phase rectifier

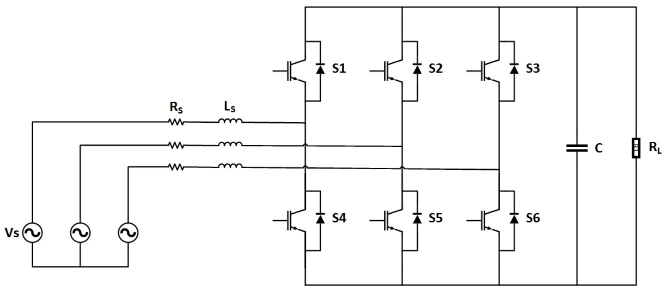


Fig. 9: Three-phase rectifier

III. Converter control

A. Single-phase rectifier

The converter control is made by using switches in parallel to the diodes in order to acquire control over the transfer of power.

The control model, shown in figure (8) is made by using two controllers, one for the output voltage and another for the input current. That is because it is not only of interest to obtain a desired dc voltage, but it is also important to have a high power factor at the input. In a more detailed way, the voltage controller is responsible to control the power that reaches the otput in order to obtain a constant voltage at the load [5]. The current controller by the other hand has the objective of producing a sinusoidal-shaped input current to the converter. To achieve this, both controllers are linked. The output of the voltage controller sets the amplitude for the input current, then by multiplying that output with a reference sinusoidal signal, the current reference for the control system is provided [6]. The output of the current controller gives the control action to the power switches. A modulation scheme is required for this purpose, a common way is to use PWM modulation techniques because of their versatility.

B. Three-phase rectifier

A three phase rectifier is composed of a three phase input, followed by a 6-switches bridge to control the power flow towards the load, figure (9) shows the circuit mentioned. As in the previous section, the control model will be concerned on both the dc output voltage and the input current. The control technique that is decided to use is known as direct power control (DPC), which basically estimates the values of active and reactive power that enters in the bridge. This control method is within the predictive control category [7]. In order to reduce substantially the complexity of the system, the $\alpha\beta$ transformation will be used. This transformation is shown in equations (7) and (8).

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = T_{\alpha\beta} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{7}$$

$$T_{\alpha\beta} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{8}$$

An important point to remark is that this transformation is valid only if the condition in equation (9) is verified.

$$x_a + x_b + x_c = 0 \tag{9}$$

Fortunately this condition is always true for symmetrical three-phase signals. It is important to notice that this transformation converts a signal of three elements into another of two elements without losing any information [8]. If the following three-phase signals are considered:

$$V_a = A \cdot sin(\omega t) \tag{10}$$

$$V_b = A \cdot sin(\omega t - \frac{2}{3}\pi) \tag{11}$$

$$V_b = A \cdot sin(\omega t + \frac{2}{3}\pi) \tag{12}$$

Using the $\alpha\beta$ transformation shown in (7) and (8), the new signals are:

$$V_\alpha = \sqrt{\frac{3}{2}} A \cdot sin(\omega t) \tag{13}$$

$$V_\beta = -\sqrt{\frac{3}{2}} A \cdot cos(\omega t) \tag{14}$$

The equation in (15) describes the behavior at the input of the rectifier [9].

$$L_s \frac{di_s}{dt} = v_s - v_{afe} - R_s i_s \tag{15}$$

Where L_s and R_s are the input line inductance and resistance respectively, i_s is the input current, v_s is the input voltage and v_{afe} is the voltage generated by the converter. Also, it is important to remark that i_s and v_s are the input line currents and voltages expressed in the $\alpha\beta$ reference such that:

$$i_s = i_\alpha + j i_\beta \tag{16}$$

$$v_s = v_\alpha + j v_\beta \tag{17}$$

The voltage v_{afe} is defined as:

$$v_{afe} = S_{afe} V_{dc} \tag{18}$$

$$\tag{19}$$

Where V_{dc} is the load voltage and S_{afe} is the switching vector, which is the $\alpha\beta$ transformation of the three switching states of the converter. If it is used the next discretization of the derivative with T_s as the sampling time:

$$\frac{di_s}{dt} = \frac{i_s(k+1) - i_s(k)}{T_s} \tag{20}$$

Then the prediction of the current in two sample steps is:

$$\begin{aligned} i_s(k+2) = F i_s(k+1) + \ldots \\ \ldots G\left[v_s(k+1) - v_{afe}(k+1)\right] \end{aligned} \tag{21}$$

Where,

$$F = \left(1 - \frac{R_s T_s}{L_s}\right) \tag{22}$$

$$G = \frac{T_s}{L_s} \tag{23}$$

For the equation (21) $v_{afe}(k+1)$ are all 7 possible voltage vectors that could be applied [9]. After calculating the predictive values for the current and voltage, active and reactive powers are calculated as shown by equations (24) and (25).

$$P_{in}(k+2) = Re\left\{v_s(k+2)\, i_s^*(k+2)\right\} \tag{24}$$

$$Q_{in}(k+2) = Im\left\{v_s(k+2)\, i_s^*(k+2)\right\} \tag{25}$$

Now, the power predictions are used to obtain the value of the cost function in (26).

$$g_{afe} = |Q_{in}(k+2)| + |P_{in}^* - P_{in}(k+2)| \tag{26}$$

Where P_{in}^* is the set point for the active power that is wanted to obtain at the input.
The control algorithm is performed so that the cost function in (26) is minimized to ensure that the input delivers a minimum reactive power and a predetermined active power. Since there exist 7 possible current predictions $i_s(k+2)$ due to the converter, 7 possible values for active and reactive powers are obtained. All these power values are used to find 7 values of the cost function, where it is chosen the one with less value and, therefore, the correspondent switching configuration is applied to the converter switches [9].

C. Three-Phase Inverter

A three-phase inverter is exactly the opposite of the three-phase rectifier for it uses a dc voltage source to produce a three-phase current output. There are several ways to control a three-phase inverter, depending basically in the modulation for the swithces and the control action. For this case, it is chosen a space vector based PWM modulation, and the control action will be executed by PI controllers. In order to achieve this, two important axis transformations are used: the $\alpha\beta$ transformation, which was explained earlier, and the

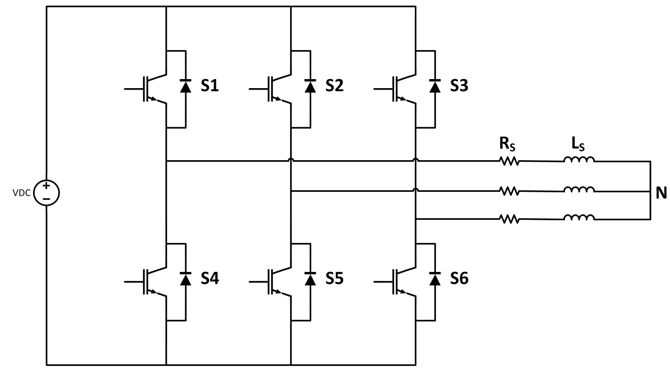


Fig. 10: Three-phase inverter

dq transformation, which will be explained soon.
In first place, space vector modulation will be explained. Space vector modulation is an algorithm used to generate PWM in three-phase converters. This is a frequently used method, for it offers several advantages regarding organization and optimization of computational resources when implementing it in a micro controller [8]. The use of space vector modulation requires that the axis of the inverter three-phase current signal to be converted in the $\alpha\beta$ reference. This implies that the load must be balanced and symmetrical in order to fulfill the condition in (9). Figure (10) shows the model of the inverter that will be considered.

For this study, ideal switches have been used to model the transistors. Notice that the load used in each phase consists of a series composition of an inductor and a resistor.
Since the space vector modulation uses the system three phase signal converted to $\alpha\beta$, the form of the output voltage of the inverter must be analyzed at each instant. If the structure of any three-phase inverter is observed, it can be noted that at any instant each phase could take two values of voltage, 0V or Vdc. If the values of the three phases are taken as components of a three-dimensional vector in the abc space, it is observed that there are only 8 possible vectors with all the combinations. Figure in (11) shows all possible voltage vectors that can be made at the output of the inverter and their respective transformation to the plane $\alpha\beta$ [8].

As can be observed in (11), all possible voltage vectors form an hexagon in the $\alpha\beta$ plane.
The fundamental strategy in the space-vector modulation is that, given any (desired) voltage vector in the $\alpha\beta$ plane, it is generated by means of the superposition of the eight possible voltage vectors such that, in average, a voltage equal to the desired is generated [8]. One way to do this is by first finding the sector of the hexagon where the desired voltage in the $\alpha\beta$ plane lies. Figure (12) shows the sectors of the hexagon numbered to give a specific order to perform the algorithm.

Subsequently, the projections of the desired voltage vector are determined in terms on the fundamental vectors of the

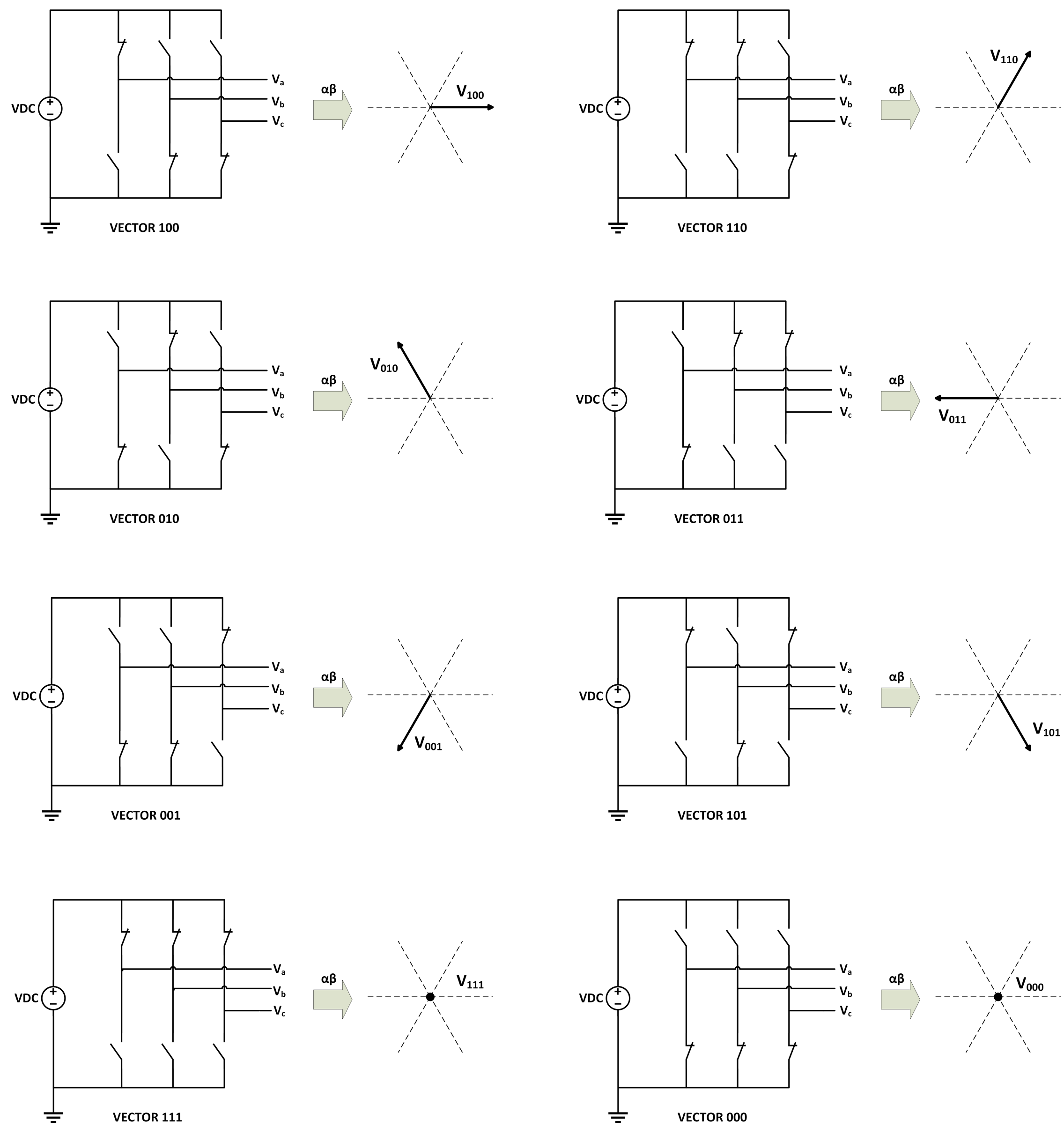


Fig. 11: Possible output voltage vectors for the three-phase inverter

correspondent sector of the hexagon as shown in figure (13).

The magnitude of the obtained projections is used to determine the fractions of the modulation period that are assigned to each fundamental vector. This information is used to design the PWM signals applied to each switch of the inverter in order to obtain the required voltage [8].

When designing the control loop for the inverter, it can be observed that the system must follow two sinusoidal references. As might be expected, it is very complicated that a system can faithfully follow a reference of such complexity [2]. This is why a further transformation, known as Park transformation or simply dq transformation, is introduced.

The $\alpha\beta$ transformation mentioned in the previous section, is a stationary axes transformation, this means that their axes do not change over time. This is not the case with the dq transformation, since its axes are rotating. The advantage of using an additional rotary axis transformation is that if the axes rotate at the same frequency as the system, constant signals will be obtained which are much easier to control by conventional methods. From two signals on the stationary reference axis $\alpha\beta$, dq transformation is defined as:

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = T_{dq} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \tag{27}$$

Where:

$$T_{dq} = \begin{bmatrix} cos\,(\omega t) & sin\,(\omega t) \\ -sin\,(\omega t) & cos\,(\omega t) \end{bmatrix} \tag{28}$$

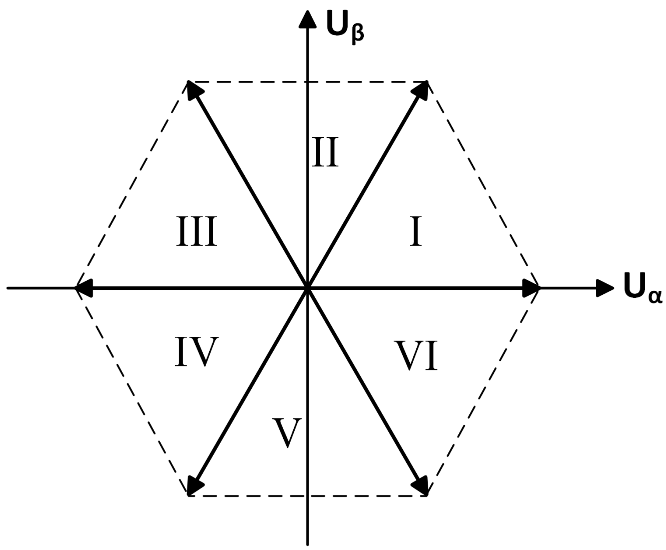


Fig. 12: Hexagon sectors in space vector modulation

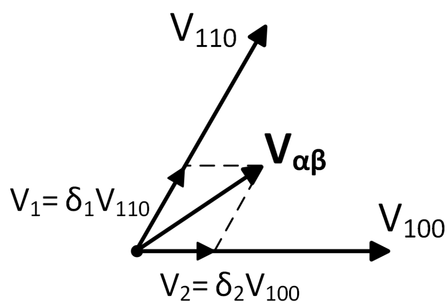


Fig. 13: Projection of the desired voltage in the fundamental vectors

If the signals from (10) to (12) are taken, and the transformation from (27) is applied with the same frequency ω, the new signals are:

$$\begin{gathered} V_d = 0 \\ V_q = -\sqrt{\tfrac{3}{2}}A \end{gathered} \tag{29}$$

Therefore, it is effectively observed that the application of this transformation over two sine waves orthogonal to each other produce two constant signals in the rotating dq plane [2].

IV. Results

A. Single-phase rectifier control simulation

A co-simulation of the control scheme shown in figure (8) is going to be performed in order to obtain a much precise result. For this purpose, Matlab Simulink and PSpice are going to be used simultaneously with the SLPS module. The schematic drawn in PSpice is shown in figure (14).

Figures (15) and (16) show the control diagram in Simulink and the results obtained respectively. The control action is made using PI controllers. Notice in figure (15) that two controllers, one for the output voltage and another for the input current, are used. The result in (16) shows the voltage output at the top and the input current at the bottom. Notice also that the current has a well sinusoidal shape, which means that the implemented current control worked properly and has not a high amount of harmonics.

B. Three-phase rectifier control simulation

The control strategy based on predictive direct power control for the three-phase rectifier is implemented in co-simulation just in the same way as with the single-phase rectifier. The model in Simulink is shown in figure (17). Where figure (18) shows the circuit in PSpice used as plant in the SLPS module. Notice in figure (17) that the parameters obtained from the SLPS module are converter to the $\alpha\beta$ reference and then linked together as a complex number.

Figures (19) and (20) show the results for two different set points. It is observed that there is a transient stage before the output of the plant stabilizes in the set point value.

C. Three-phase inverter control simulation

The simulation of the current control system for the three-phase inverter is performed using the same strategy as in the previous section, with custom blocks designed with S-Functions in the Simulink model in order to implement the modulator and the transformations that are needed. Figure in (21) shows the circuit designed with PSpice which will be used as the plant for the control loop.

The Simulink simulation model is shown in figure (22). As can be seen, the current leaving the plant is converted to the $\alpha\beta$ coordinates, to be then converted to the rotational coordinates dq. The set points are entered in dq coordinates and then go through the PI controllers. Finally, the signals are returned to the $\alpha\beta$ coordinates before they enter to the modulator. Figures (23) and (24) show the results obtained for two different set points.

V. Conclusions

The mathematical model of the single-phase rectifier was satisfactorily obtained and tested. The dynamic behavior of the uncontrolled rectifier is highly non-linear for the input current, so correctly implementing the conditions to solve the equations in numerical form carries a high complexity. The control loop for the single-phase rectifier was implemented correctly by means of co-simulation, the strategy of simultaneous control of voltage and current was effective, as well as the use of SPWM modulation. Also, the implementation of predictive control over the three-phase rectifier was successful, the use of the $\alpha\beta$ transformation helped to significantly simplify the model

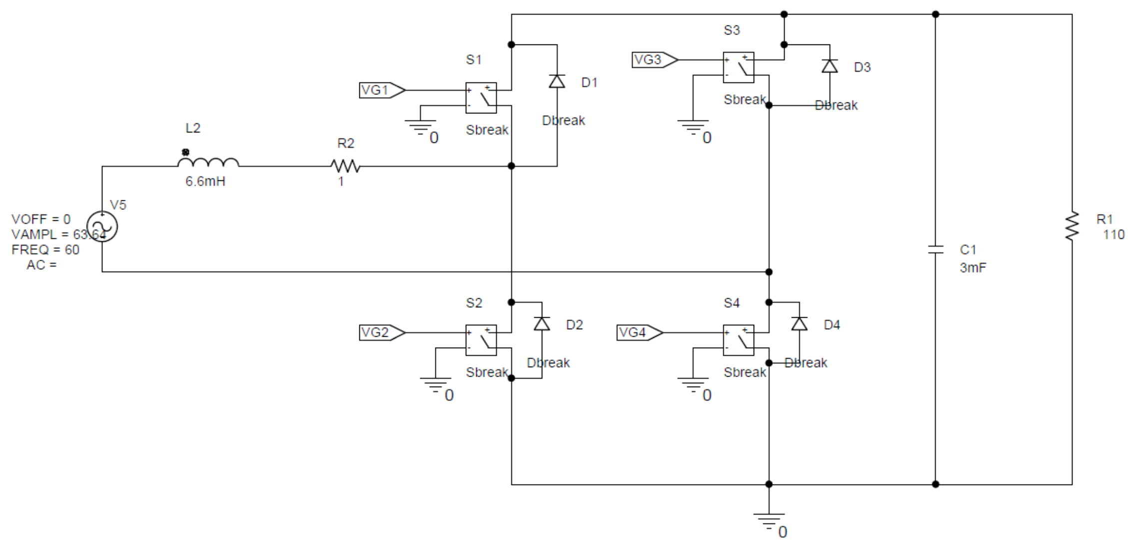


Fig. 14: Controlled single-phase rectifier

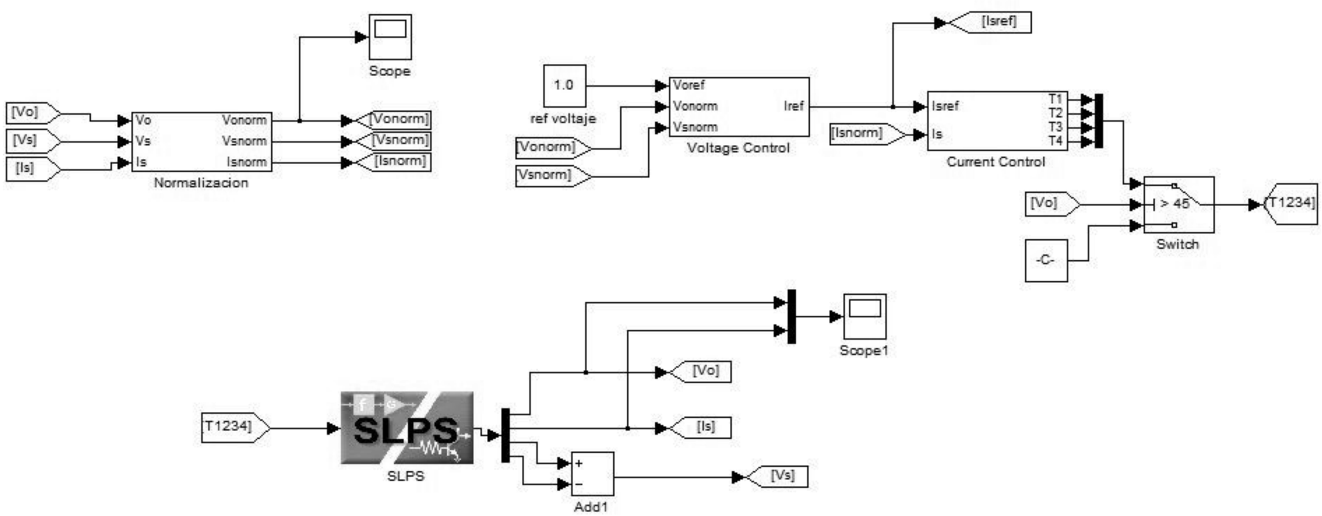


Fig. 15: Single-phase rectifier voltage control diagram in Simulink

equations. Using the predictive model in two sampling times of advance did not show inconveniences in the convergence of the output. The control of the three-phase inverter was effectively implemented in co-simulation, the use of vector space modulation was efficient to determine the correct switching times of each power switch. Using the $\alpha\beta$ and dq transformations was of great help to simplify and optimize the control system. As a final remark, SLPS module was used, which is a new product that recently came on the market to perform co-simulation, so it was verified its effectiveness to carry out the simulations for the control systems of interest and therefore it is encouraged to continue using this module for future research.

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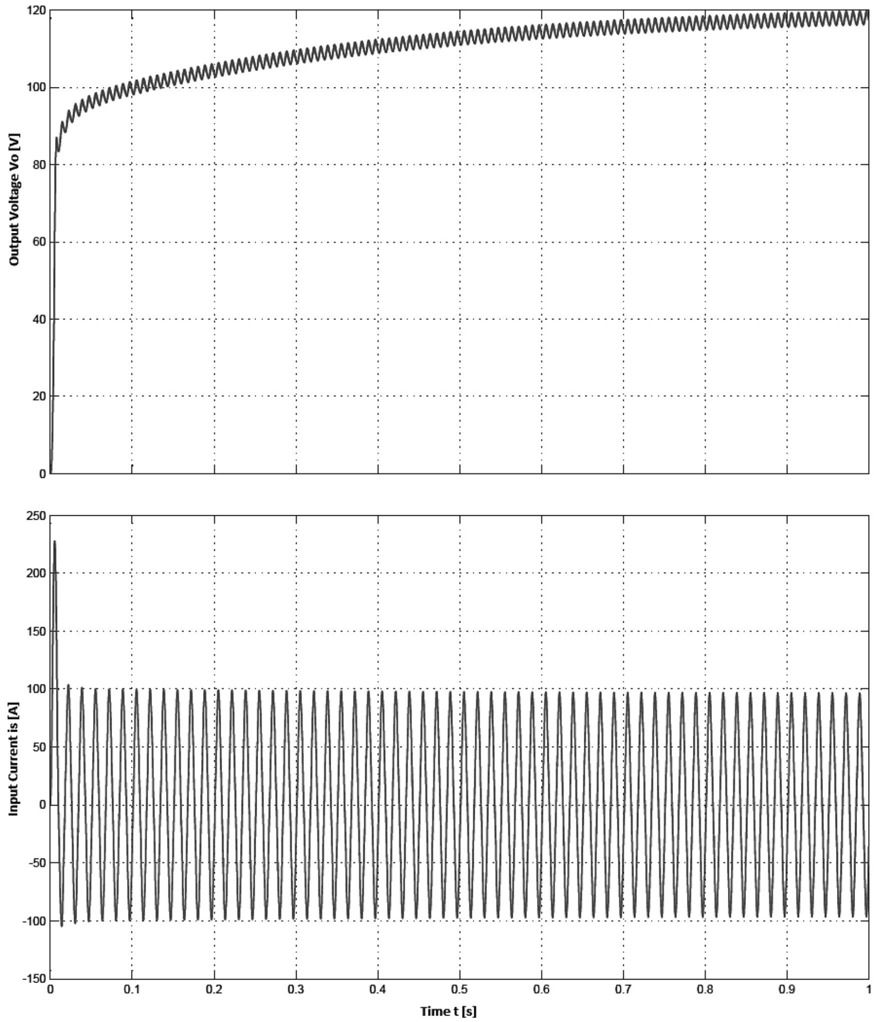

Fig. 16: Voltage control of single-phase rectifier, simulation result

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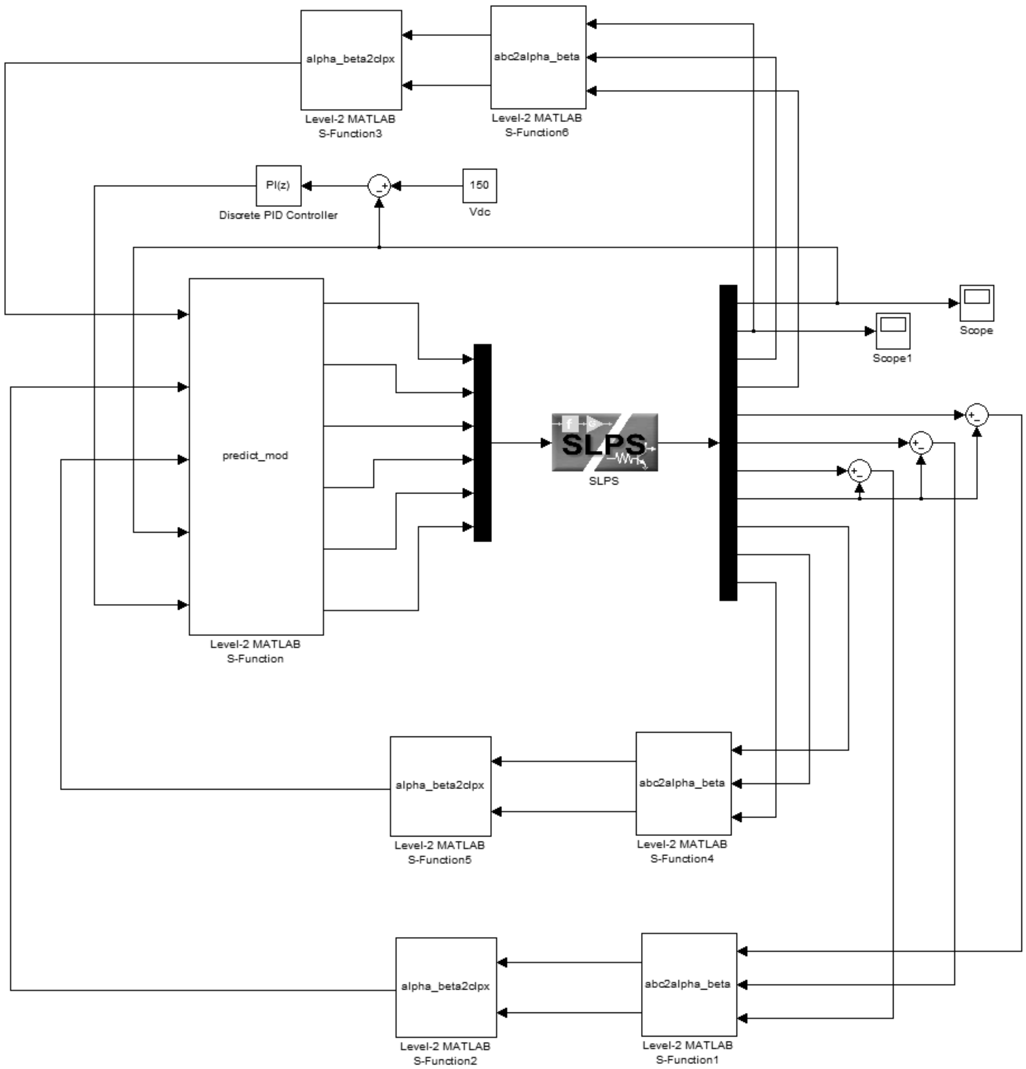

Fig. 17: Simulation of predictive control for the three-phase rectifier.

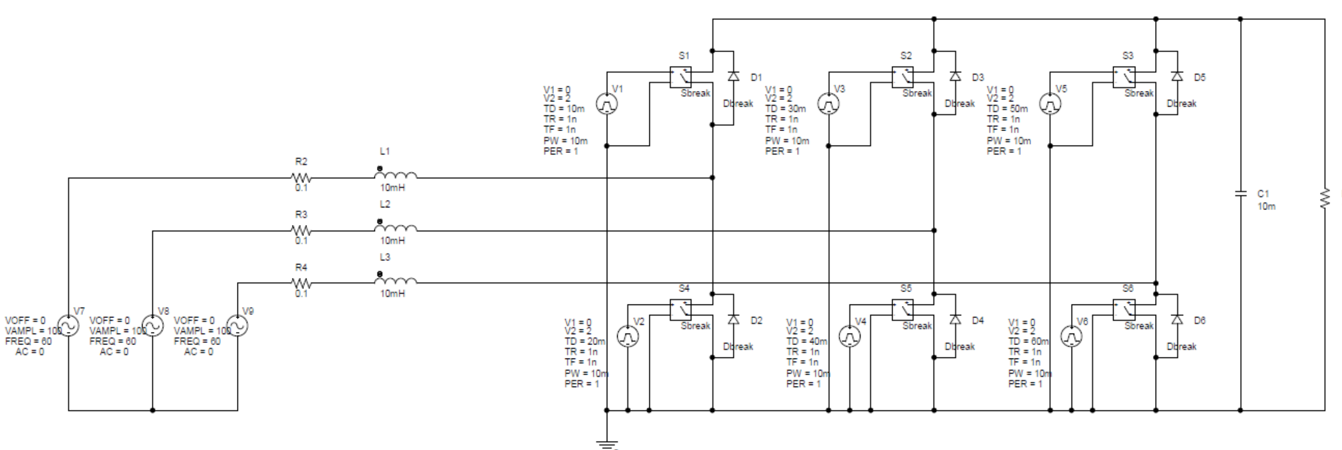

Fig. 18: Three-phase rectifier circuit in PSpice

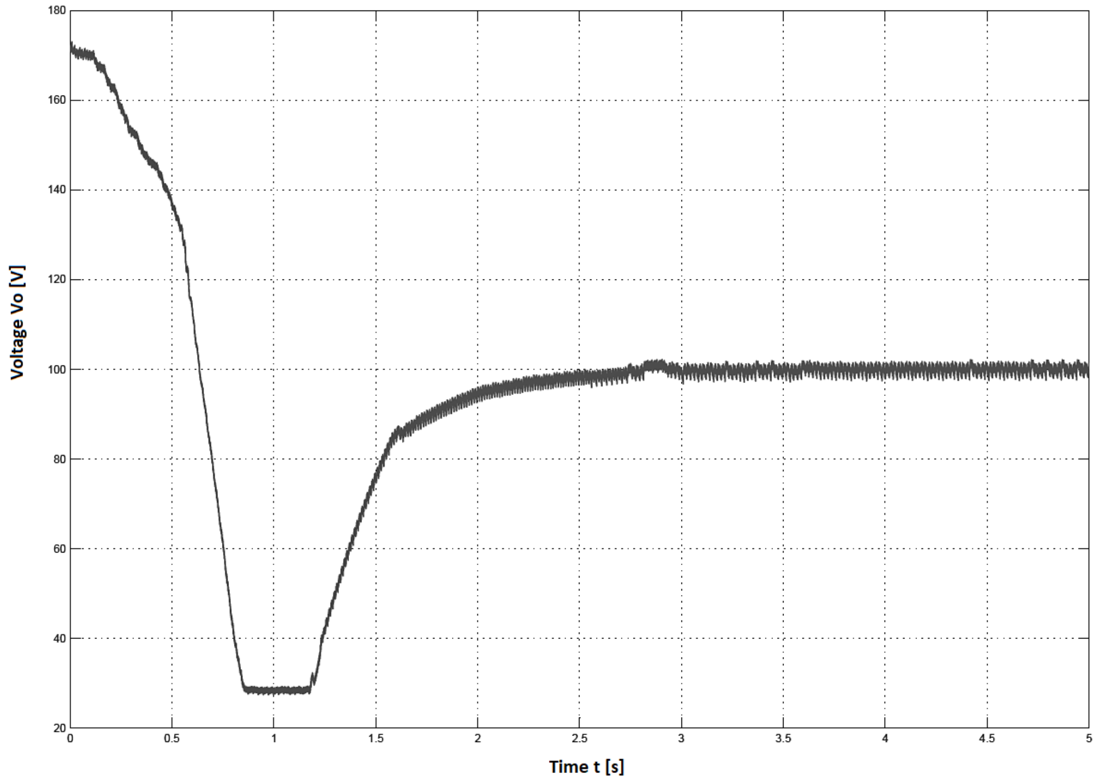

Fig. 19: Simulation result for the three-phase rectifier control system. Set point of 100 [V]

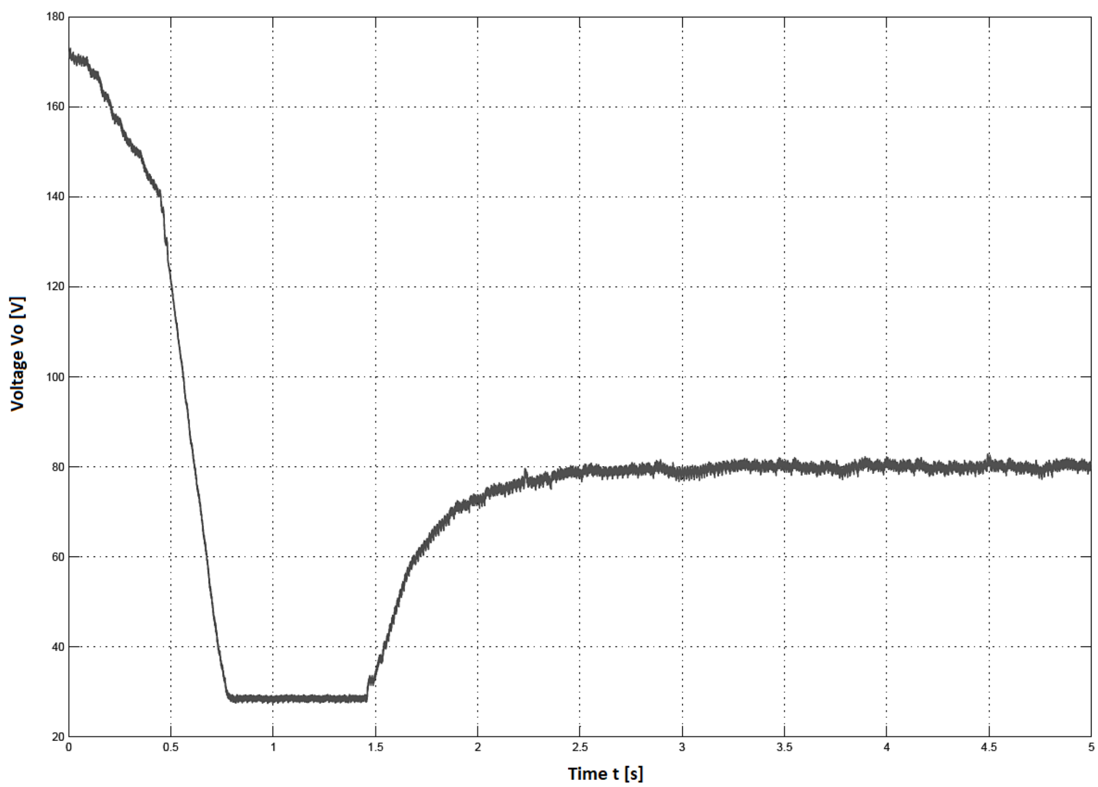

Fig. 20: Simulation result for the three-phase rectifier control system. Set point of 80 [V]

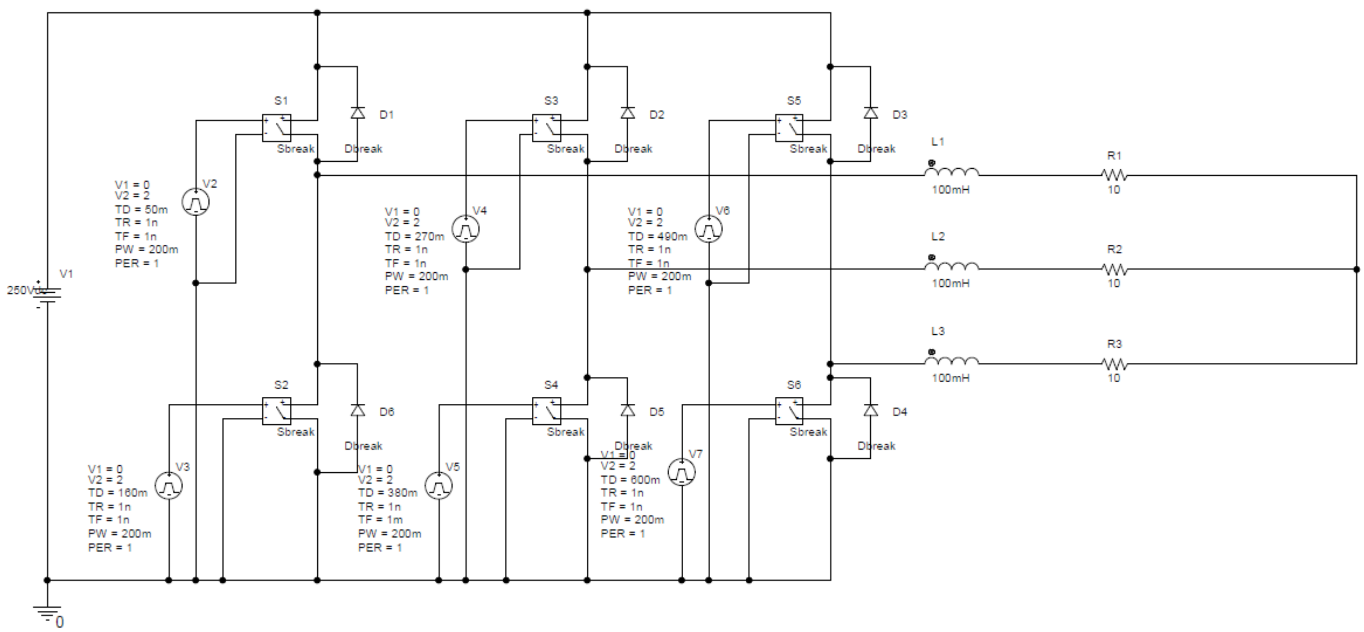

Fig. 21: Inverter circuit in PSpice used for co-simulation.

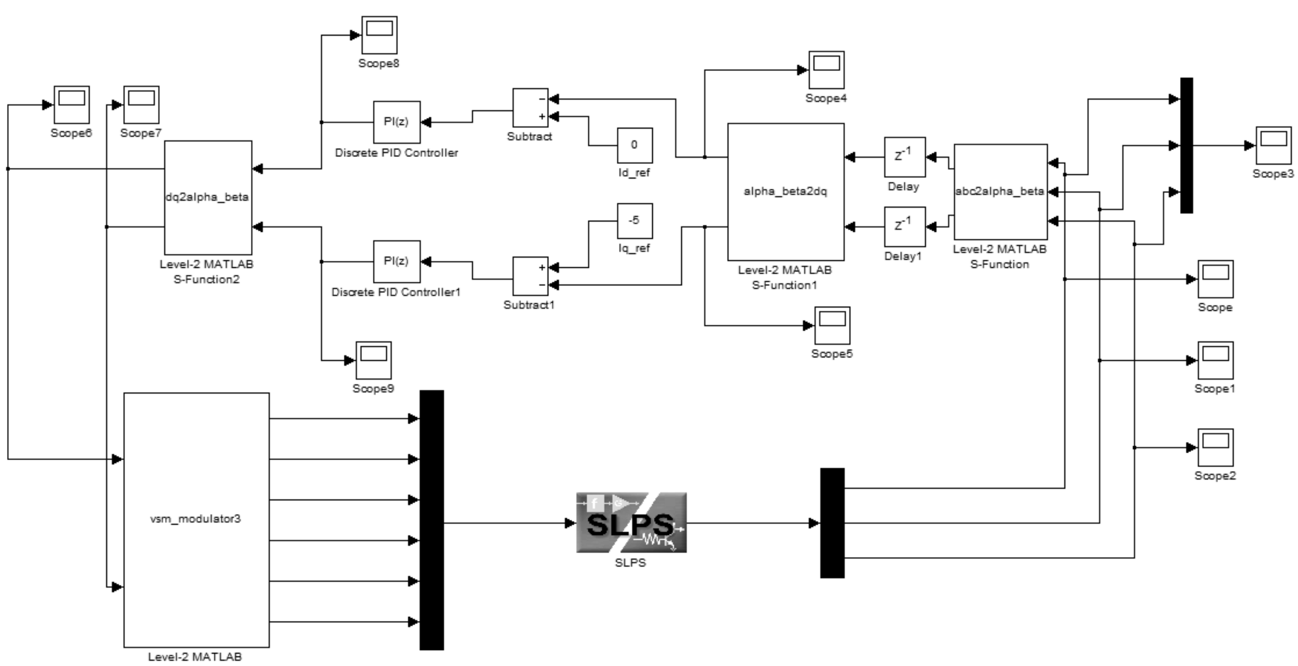

Fig. 22: Simulink model of the current control loop for the inverter.

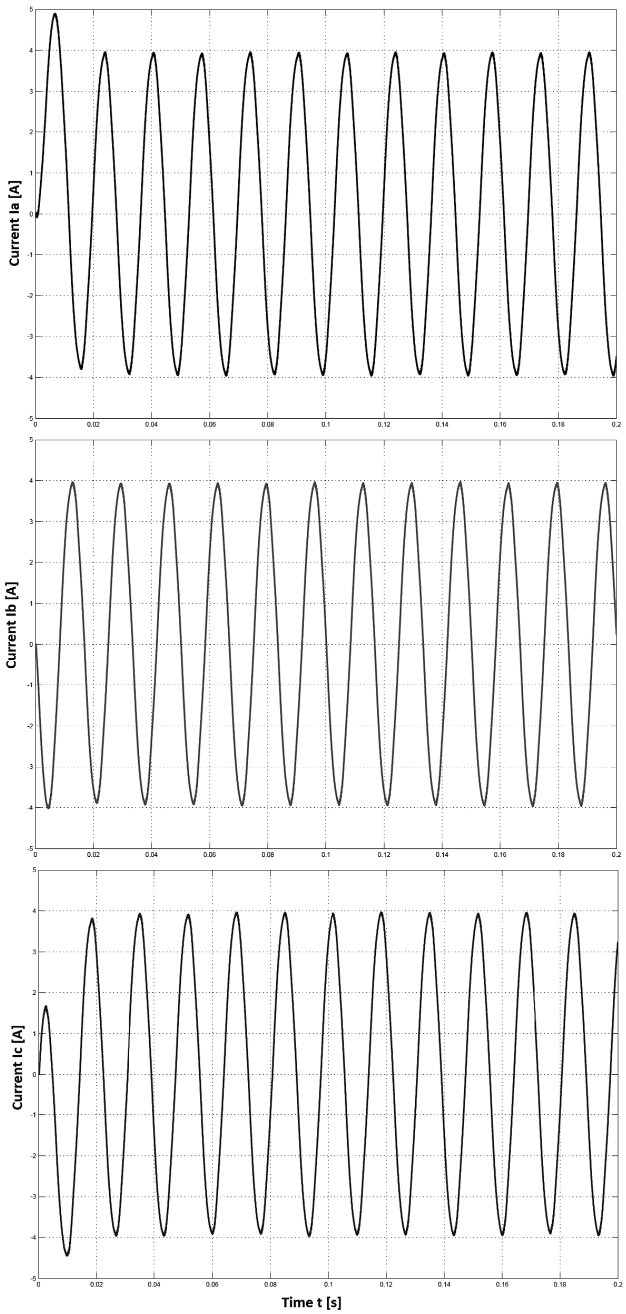

Fig. 23: Simulation result for the three-phase inverter control system. Set point of 4[A]

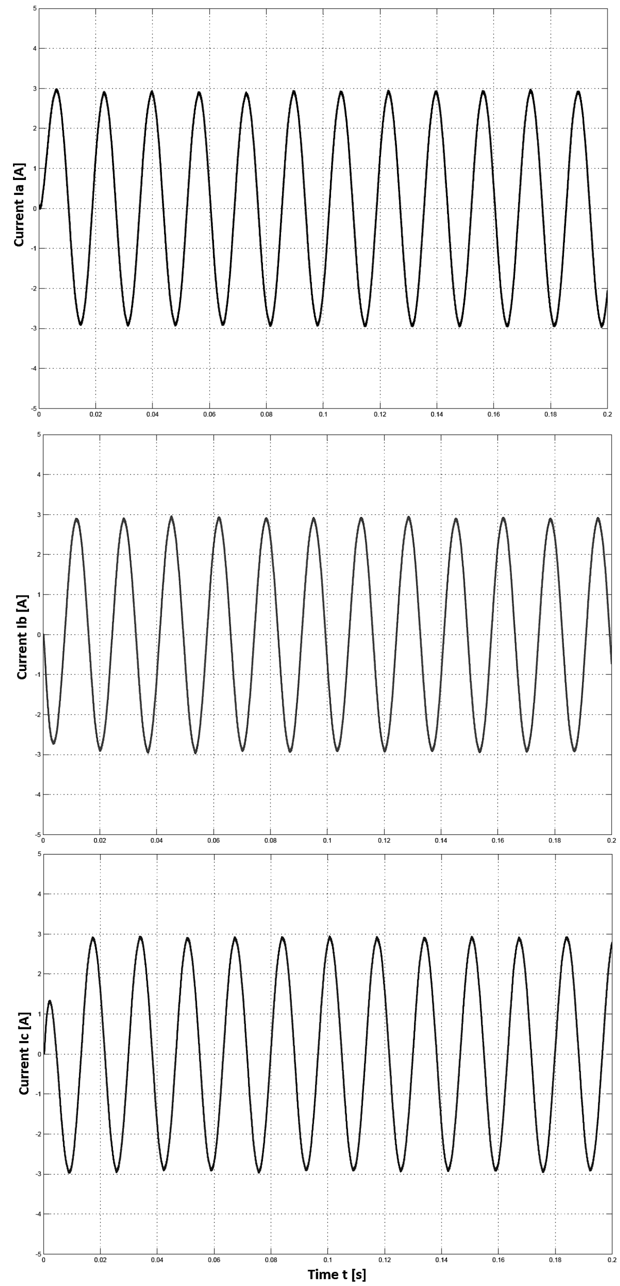

Fig. 24: Simulation result for the three-phase inverter control system. Set point of 3[A]