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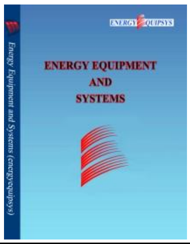

Power injection of renewable energy sources using modified model predictive control

Authors

Seyed Seraj Hamidi [a*]
Hossein Gholizade-Narm [a]

[a] Department of Electrical and Robotic Engineering, Shahrood University of Technology, Shahrood, Iran

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ABSTRACT

This paper presents a simple model predictive control (MPC) approach to control the power injection system (PIS) for renewable energy applications. A DC voltage source and a single-phase inverter that is connected to the grid by an LCL filter form the PIS. Grid voltage is considered a disturbance for the system. For eliminating this disturbance, a modified model is proposed. It is usual to control output current to inject a desired power to grid. But due to the presence of the LCL filter, we face a third-order system and other states should be bounded during operation. In this work, we ensure the stability of other state variables and, consequently, system stability, by defining a proper cost function. In this regard, reference signals are calculated for all state variables. For getting the benefit of the switching nature of the inverter, we use a finite control set model predictive control (FCS-MPC). Proposed predictive control is implemented in a digital scheme and, thereby, the discrete model of the system is extracted. The proposed controller does not require any other control loop or modulation method. Simulation results show the effective performance of the proposed control scheme.

Keywords: Finite Control Set Model Predictive Control (FCS-MPC), Power Injection System (PIS), LCL Filter, Voltage Source Inverter (VSI), Renewable Energy.

1. Introduction

Increasing demand worldwide for electrical energy and the environmental pollution of fossil fuels are the current concerns of modern society. Such issues have led to the creation of laws and policies by governments regarding the use of alternative energies. Renewable energy sources (RESs), such as solar, wind, biomass, fuel cells, and geothermal, are faced with better conditions to generate electrical power [1]. That is, the use of renewable energy sources such as photovoltaic (PV) systems has increased [2].

Some typical RESs, such as PVs, generate a DC voltage that is not regulated or not at a proper level for conversion. In such cases, an uncontrolled and unregulated DC input voltage is filtered and regulated depending on specific load requirements. Different types of DC/DC converters are utilized for this purpose. These converters are generally used in PV systems [3]. The fixed output voltage is sometimes called a DC link and it can be assumed as a voltage source.

The majority of renewable energy systems are used as grid-connected power sources [4]. This is due to the advantages of grid-connected systems and their role in new issues such as smart grids and other emerging technical topics in modern power systems.

*Corresponding author: Seyed Seraj Hamidi
Address: Department of Electrical and Robotic Engineering, Shahrood University of Technology, Shahrood, Iran
E-mail address: hamidi@ieee.org

Grid integration of RESs faces challenges as usual. One of the most known and damaging phenomena in power sources that are connected to the electrical network is harmonic generation. These harmonics can be considered the main cause of damage to sensitive equipment. According to the IEEE-1547 standard, total harmonic distortion (THD) of the injected current into a grid should be less than 5%. There are two reasons for harmonic generation. The first comes from the nature of the inverter, such as pulse width modulation (PWM) and switching. The second reason relates to load and grid [5].

A common way to eliminate harmonics is by using a low-pass filter between the inverter and the electrical grid. There are several types of filters for this purpose. The simplest filter for harmonic elimination is an inductor that is connected to the inverter output. However, filter performance can be improved by adding a capacitor to the filter. LC and LCL are the most common of these. Among the mentioned methods (L, LC, and LCL filters) to eliminate harmonics, the LCL filter is considered for two reasons: First, LCL filters have better damping compared to LC filters of the same size; second, LCL filters have an output inductor at the point of connection to the grid that prevents inrush currents [6]. However, despite the good performance of LCL filters in harmonics elimination, the use of these filters is not without challenges. L and LC filters have simpler design and control procedures compared to LCL filters. This is because LCL filters increase the order of the system that should be controlled and require designing more efficient controllers. This makes the controller design procedure more complex [7].

In fact, the main objective in control of the grid-connected inverter is tracking of a sinusoidal reference current with low THD. Until now, many different methods for controlling grid-connected inverters have been introduced [8]. Undoubtedly, one of the most popular of these controllers is the proportional-integral (PI) controller. This controller faces two major problems: steady-state error and inefficiency in disturbance rejection [9]. To fix the problem, the proportional-resonant (PR) controller has been proposed [10]. The PR controller, by applying the gain in a desired (resonant) frequency, reduces the steady-state error at that frequency. The gain of a PR controller is infinite at resonant frequency. This is the main drawback of a PR controller. To overcome this problem, [11] applied a feed-forward from the grid voltage. But by applying this technique, harmonics is injected from the grid to the current [12]. References [13] and [14] used linear- and nonlinear-state feedback, respectively, and investigated system stability. Sliding mode control is proposed in [15] but it is complicated in theory.

In recent years, attention to the model predictive control (MPC) has increased in the field of power electronics. That is because this control strategy can handle system limitations such as nonlinearity, multi-variability, and various system constraints [16]. Different methods have used MPC for power electronics converters [17, 18]. For example, in [19], an explicit MPC is applied to an inverter with an LCL filter. This method is based on a hybrid model of a system that is theoretically complicated and, furthermore, that requires a modulator for practical implementation. Another MPC method is finite control set model predictive control (FCS-MPC) [20]. This method is theoretically simple and uses the switching nature of power converters. A significant advantage of FCS-MPC is that control signals apply to the system directly and no modulator is required. In this paper, our proposed controller is based on the FCS-MPC concept.

The rest of this paper is organized into four sections: In Section 2, the state space model of PIS is obtained and then a modified model for disturbance rejection is extracted. The controller design is detailed in Section 3. A discrete-time model for prediction, the reference design, and the control algorithm are presented in this section. Finally, the simulation results and the conclusion are presented in Sections 4 and 5, respectively.

2.Modelling of Power Injection System

2.1.Description of the System

A power-circuit diagram of a PIS, which consists of a DC voltage source and a grid-connected voltage source inverter (VSI) with the LCL filter used in this work, is shown in Fig.1. The DC voltage is provided by solar cells, for example. We assume the output of cells is boosted and regulated by using a boost DC/DC converter. This voltage source is represented by V_{dc}. As can be seen in Fig. 1, the inverter is a single-phase full bridge consisting of four power switches connected to the grid by an LCL filter.

T_1, T_2, T_3, and T_4 are transistors that control the VSI. R_1, L_1, R_2, and L_2 are series-resistance and inductance of both sides of the filter and its parallel capacitance and resistance are C and R, respectively. Also, v_g is the grid voltage.

2.2.State-space Model

There are 2^4=16 combinations based on the number of switches and their operation modes (OFF or ON) for VSI operation. According to the basic electrical circuits theory, the possible switching states that can occur are four, as shown in Table 1.

An equivalent circuit of the PIS is shown in Fig.2. In this figure, $v_{inv}(t)$ is the output voltage of the inverter and we assume it is a new input for the equivalent circuit. It can be expressed based on the DC input voltage as

$$v_{inv}(t) = (S_a(t) - S_b(t))V_{dc} \quad (1)$$

where $S_a(t)$ and $S_b(t)$ are defined as switches variables for each leg of the inverter and can be 0 or 1 according to Table 1.

From Fig. 2, we can write Kirchhoff's laws for the circuit. Thus, the dynamics of the PIS can be expressed as the following equations:

$$i_1(t) - i_2(t) - C\frac{dv_C(t)}{dt} = 0 \quad (2)$$

$$R_1 i_1(t) + L_1\frac{di_1(t)}{dt} + v_C(t) + R\left(i_1(t) - i_2(t)\right) - v_{inv}(t) = 0 \quad (3)$$

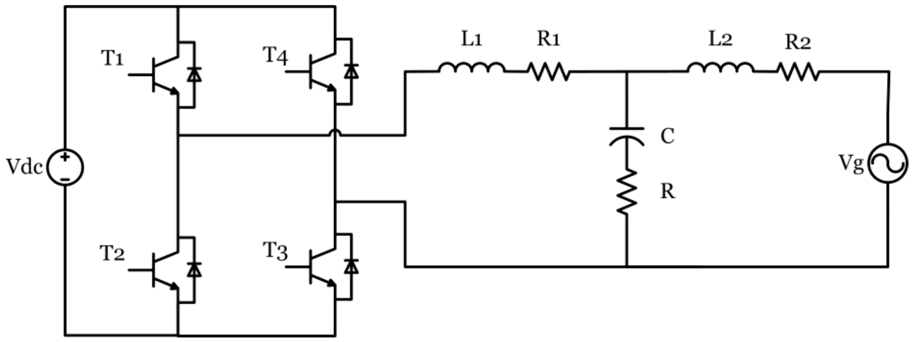

Fig.1. Schematic of LCL-based grid-connected inverter

Table 1. Feasible switching states of the inverter

Switches Operation				Switches Variables	
T_1	T_2	T_3	T_4	$S_a(t)$	$S_b(t)$
OFF	ON	ON	OFF	0	0
OFF	ON	OFF	ON	0	1
ON	OFF	ON	OFF	1	0
ON	OFF	OFF	ON	1	1

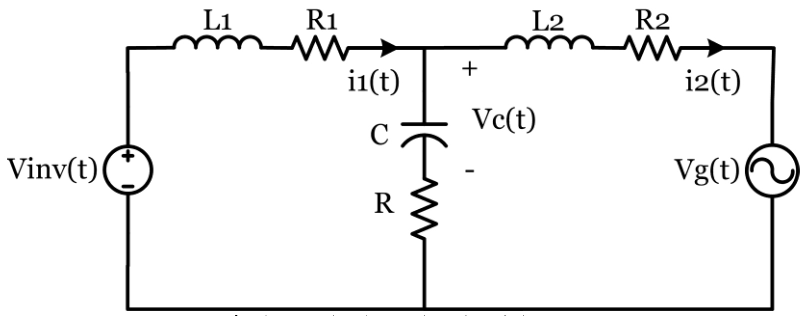

Fig.2. Equivalent circuit of the PIS

$$R_2 i_2(t) + L_2 \frac{di_2(t)}{dt} + v_g(t) + R\left(i_2(t) - i_1(t)\right) - v_C(t) = 0 \tag{4}$$

where $i_1(t)$, $i_2(t)$, and $v_C(t)$ are the series inductor currents and capacitor voltage of the filter, respectively.

These equations can be rewritten as a linear time-invariant (LTI) system in state-space form as

$$\frac{dx(t)}{dt} = Ax(t) + Bu(t) + B_g w(t) \tag{5}$$

where

$$x(t) = \begin{bmatrix} v_C(t) \\ i_1(t) \\ i_2(t) \end{bmatrix}$$

$$u(t) = v_{inv}(t),\ w(t) = v_g(t)$$

and

$$A = \begin{bmatrix} 0 & \frac{1}{C} & -\frac{1}{C} \\ -\frac{1}{L_1} & -\frac{1}{L_1}(R+R_1) & \frac{R}{L_1} \\ \frac{1}{L_2} & \frac{R}{L_2} & -\frac{1}{L_2}(R+R_2) \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ \frac{1}{L_1} \\ 0 \end{bmatrix},\ B_g = \begin{bmatrix} 0 \\ 0 \\ -\frac{1}{L_2} \end{bmatrix}$$

This system is a third-order dynamic system with quantized input $v_{inv}(t)$. The grid voltage can be considered as a disturbance in this model. The next section deals with this issue.

2.3. Modified Model for Disturbance Rejection

The grid voltage in the state-space model (5) appeared as a disturbance, considering that the input of the system is an inverter output voltage. With the presence of this term in the model, calculations and controller design will become more complicated. We will eliminate this term considering the desired active power. To remove the disturbance completely, the physical effect of this signal on system states should be considered and then changes applied to the model. In this way, $i_1(t)$ and $i_2(t)$ are affected by grid voltage and desired power. But these effects are complicated to compute directly and accurately. We use a simpler approximation for disturbance rejection. In this work, we will inject an active power into the grid. Assume that the desired output active power is P. The output current $i_2(t)$ and the grid voltage $v_g(t)$ should also be synchronized with zero phase difference to deliver pure active power to the grid. Therefore, in steady state, we have:

$$v_g(t) = V_m \sin(\omega t) \tag{6}$$

$$i_{2ss}(t) = I_m \sin(\omega t) \tag{7}$$

and by writing active power P as:

$$P = \frac{1}{2} V_m I_m \tag{8}$$

we can obtain output current in terms of grid voltage:

$$v_g(t) = K_{vi} i_{2ss}(t) \tag{9}$$

$$K_{vi} = \frac{2P}{I_m^{\ 2}} \tag{10}$$

where $i_{2ss}(t)$ is the output current steady state. By substituting $v_g(t)$ within $K_{vi} i_{2ss}(t)$ in the state-space model (5), the modified model obtained is as follows:

$$\frac{dx(t)}{dt} = A_m x(t) + Bu(t) \tag{11}$$

where

$$A_m = \begin{bmatrix} 0 & \frac{1}{C} & -\frac{1}{C} \\ -\frac{1}{L_1} & -\frac{1}{L_1}(R+R_1) & \frac{R}{L_1} \\ \frac{1}{L_2} & \frac{R}{L_2} & -\frac{1}{L_2}(R+R_2+K_{vi}) \end{bmatrix}$$

and other variables and parameters are the same as defined in the state-space model (5).

3. Controller Design

The proposed control strategy for PIS is described in this section. This control is based on FCS-MPC. A block diagram of the control strategy that applied to the PIS is shown in Fig. 3.

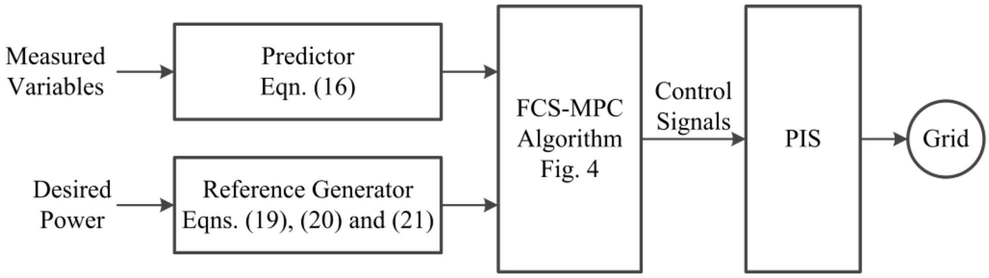

Fig.3. Proposed control scheme for PIS

The predictor block is based on a discrete-time model of the system and predicts system states for the next sampling time. The reference generator consists of equations based on design requirements and desired variables. These two blocks provide the desired and predicted controlled variables to the FCS-MPC block. The FCS-MPC algorithm is illustrated in Fig. 4. The tracking error between predicted and desired variables is computed in the next sampling interval for each feasible switching operation with regard to a pre-defined cost function. The output voltage of inverter $v_{inv}(t)$ that minimizes the error is selected and then corresponding switches states applied to the inverter. This procedure repeats in the next sampling intervals.

Cost function definition, discrete-time model for prediction, and reference generation are detailed in the following subsections.

3.1.Cost Function Definition

The cost function's main objective is to track a particular variable and control the system. In the literature, different cost functions have been used in MPC design procedure [21]. These are based on the control specifications and requirements, such as current tracking, active and reactive power control, switching frequency minimization, and so on. These cost functions are detailed in [22]. Common forms of cost functions are

$$J = \left| x_p - x^* \right| \tag{12}$$

$$J = \left(x_p - x^* \right)^2 \tag{13}$$

$$J = \frac{1}{T_s} \int_{T_s} \left(x_p(t) - x^*(t) \right)^2 \tag{14}$$

where x^p and x^* are predicted and reference variables, respectively. In this work, the cost function (12) is considered. This is the sum of

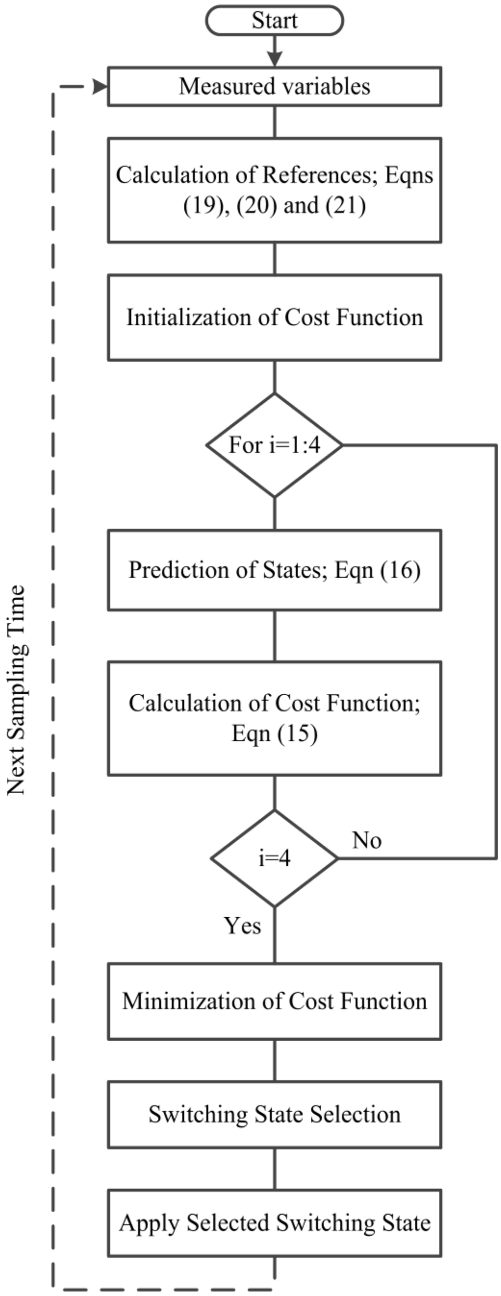

Fig.4. FCS-MPC algorithm

the absolute values of states error between predicted and reference variables. For control of PIS, it is proposed as the following:

$$J = w_1 \left| i_1(k+1) - i_1^*(k+1) \right| + w_2 \left| i_2(k+1) - i_2^*(k+1) \right| + w_3 \left| v_C(k+1) - v_C^*(k+1) \right| \quad (15)$$

where w_i, i=1, 2, 3 are weight factors for each state variable. This cost function is easier to compute compared to other cost functions that increase control system performance. Besides this, our goal is to control injected power to the grid by controlling the inverter output current $i_2(t)$. With output current tracking, we will achieve our goal. But due to the presence of the LCL filter, there are two other state variables that should be bounded during operation. If we form the cost function only based on output current, other state variables may be unstable [23]. This definition of cost function ensures stability of state variables.

3.2.Discrete-time State-space Model for Prediction

For implementing control algorithms of digital control systems, it is necessary to discretize the continuous-time model of the system. Several discretization methods can be used in order to obtain a discrete-time model that is suitable for the calculation of predictions in FCS-MPC either approximately or exactly [24, 25]. The results of approximation discretization methods, such as Euler-forward and Euler-backward discretization, are suitable and accurate for simple systems. However, if the sampling times become too long, this approximation of systems can become unstable. Euler approximations are useful for obtaining a discrete model. However, for more complex systems with a higher order, this approximation method may be accompanied with unacceptable error in the model. When dealing with more complex systems with a higher order, such as control of PIS in this work, more accurate discretization methods are required [19]. Especially for LTI systems, it is possible to discretize the continuous- time model exactly for a given sampling time. Zero-order hold (ZOH) is an exact method for extracting a discrete-time model of the system. From the state-space modified model (11), and using the ZOH method with the sampling time T_s, we can obtain the following discrete-time model [26]:

$$x(k+1) = A_d x(k) + B_d u(k) \quad (16)$$

where $k=t/T_s$ is the current sampling period and the discrete system matrices are:

$$\mathrm{A_d} = \mathrm{e}^{\mathrm{A}_m \mathrm{T_s}} \quad (17)$$

$$\mathrm{B_d} = \int_0^{\mathrm{T_s}} \mathrm{e}^{\mathrm{A}_m \eta} B d\eta \quad (18)$$

The model given in (16) is an exact discrete-time model for the continuous-time system. This discrete-time model will be used to predict the future value of state variables from measured states at the K^{th} sampling interval.

3.3.Reference Design

As mentioned, all system state variables are in the cost function and the corresponding references should be calculated to determine the best switching action. For a given desired active power P and existing grid voltage amplitude V_m, from Eq. (8) we can obtain a grid-side current reference as:

$$i_2^*(t) = I_{2m}^* \sin \omega t \quad (19)$$

where $I_{2m}^* = \dfrac{2P}{V_m}$.

By substituting (19) in the two following equations that have been extracted from the modified model, we can obtain references for $i_1(t)$ and $v_C(t)$:

$$i_1^*(t) - i_2^*(t) - C \frac{dv_C^*(t)}{dt} = 0 \quad (20)$$

$$L_2 \frac{di_2^*(t)}{dt} + (R + R_2 + K_{vi}) i_2^*(t) - R i_1^*(t) - v_C^*(t) = 0 \quad (21)$$

where $i_1*(t)$ and $v_C*(t)$ are references for $i_1(t)$ and $v_C(t)$, respectively.

4.Simulation Results

Performance of the proposed modified MPC method for the PIS is tested using MATLAB/Simulink software. In order to verify the proposed control strategy, a regulated DC voltage source of 400 V is considered and active power reference is assumed to be 11 kW. It is assumed that grid voltage is a pure sine wave of 312 V amplitude and 50 Hz frequency. Parameters of the LCL filter are selected as in Table 2 [27].

The sampling time for discretization is T_s=10μs and the sampling time for implementation of FCS-MPC has been chosen as 20μs, which is easily achievable for practical implementations. In addition, the weight factors equal to one for all states.

Figure 5 shows the reference and controlled injected current to the grid and the tracking error between them. From the figure, it appears that the tracking is appropriate. In addition, the results show that the injected current to the grid has a high quality and the corresponding THD is less than 1%.

Figure 6 shows that the grid-side current $i_2(t)$ tracks a pure sinusoidal signal in phase synchrony with the grid voltage. This means that the output power is a pure active power.

Table 2. LCL filter parameters [27]

Description	**Parameter**	**Value**
Inverter-side inductance	L_1 R_1	1 [mH] 0.1 [Ω]
Grid-side inductance	L_2 R_2	2 [mH] 0.2 [Ω]
Capacitor	C R	5 [µF] 5 [Ω]

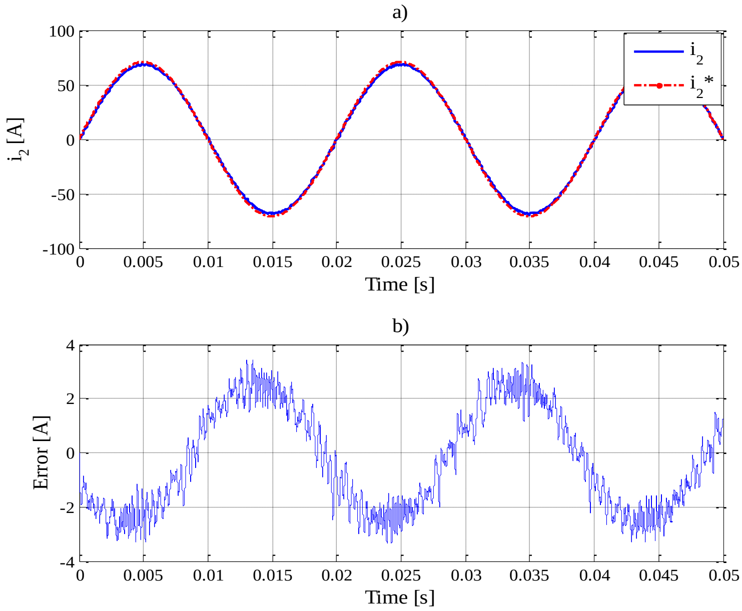

Fig.5. a) Reference and actual output current; b) tracking error

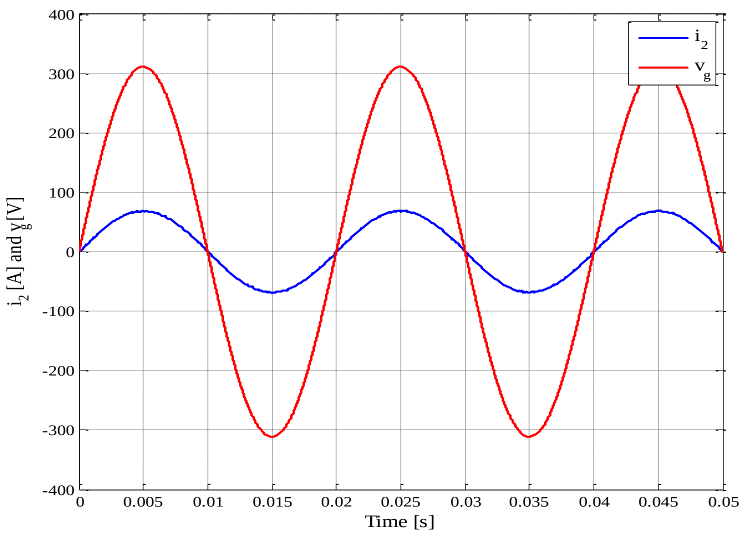

Fig. 6. Current and voltage of grid

As mentioned, the proposed method ensures that all states are bounded. This can be seen in Fig. 7. That shows the current of the inverter-side inductor and the voltage of the capacitor based on the output current in the phase plane. As the figure shows, all the states remain bounded and are in a stable limit cycle.

Figure 8 shows the performance of the grid-side current during a step change in desired power from 11 kW to 8kW. As can be seen, the output tracks the reference current with a good behaviour despite the power step change and verifies the effectiveness of the proposed controller. It is notable that during the step change in reference power, all three state references change instantaneously based on reference generation dynamics (Eqs.(19), (20), and (21)) and the control system adapts to the new condition.

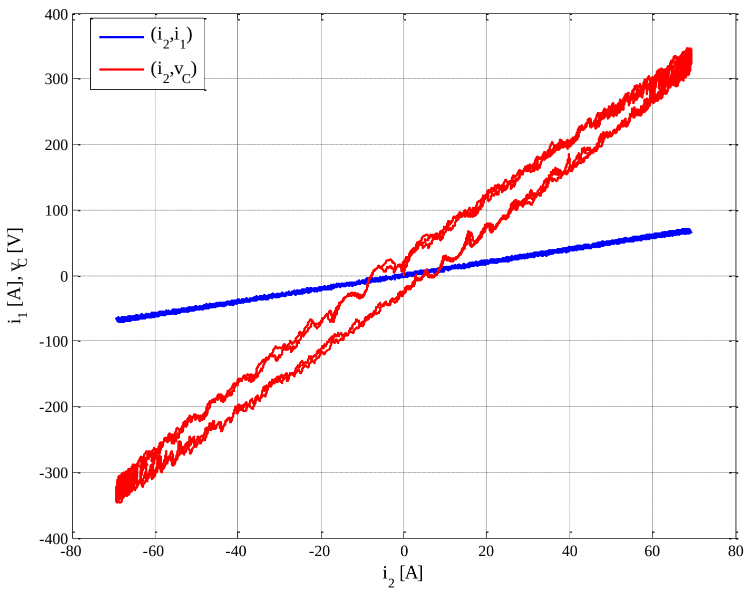

Fig. 7. Phase plane (i_2,i_1) and (i_2,v_C)

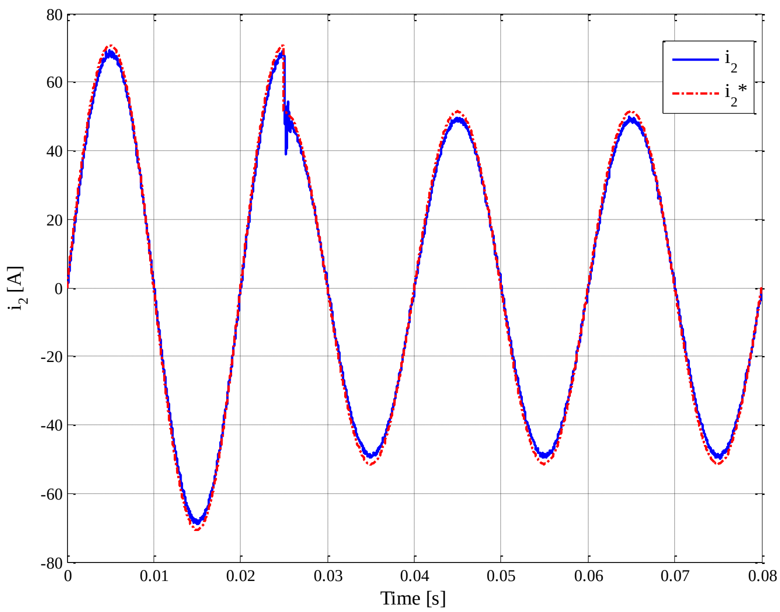

Fig.8. Grid-side current during a step change in reference power

5.Conclusion

The goal of this paper was to present a method to control a grid-connected LCL-filtered voltage source inverter. The controller was within an FCS-MPC framework. All computations have done with regard to the modified model that was established for disturbance rejection. The proposed controller does not require any other control loop or modulator. A cost function was designed that was easy to compute and that ensured the stability of the system. Although inverters with LCL-based filters require more complex control strategies, the proposed controller was simple and easy to implement. Furthermore, the proposed control injected a high-quality current to the grid and worked well during the change in desired power. The effectiveness of the operation of the controller was demonstrated through the simulations.

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