UNIVERSIDADE FEDERAL DE SANTA MARIA
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# CONTROLE PREDITIVO DE ESTADOS FINITOS BASEADO NA TEORIA P-Q PARA REGULAÇÃO DE TENSÃO E COMPENSAÇÃO DE HARMÔNICOS EM UM GIAE ISOLADO

Santa Maria, RS
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Trabalho de Conclusão de Curso apresentado ao Curso de Engenharia Elétrica, da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para obtenção do título de **Bacharel em Engenharia Elétrica.**

Orientador: Prof. Dr. Robinson Figueiredo de Camargo

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Marcos Vinicius Soares Gonçalves

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Aprovado em 29 de agosto de 2022

________________________________________
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**(Presidente/Orientador)**

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**Gabriel Maier Cocco, Me. (UFSM)**

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**Carlos Antônio de Souza, Me. (UFSM)**

Santa Maria, RS
2022

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# RESUMO

## CONTROLE PREDITIVO DE ESTADOS FINITOS BASEADO NA TEORIA P-Q PARA REGULAÇÃO DE TENSÃO E COMPENSAÇÃO DE HARMÔNICOS EM UM GIAE ISOLADO

AUTOR: Marcos Vinicius Soares Gonçalves
ORIENTADOR: Robinson Figueiredo de Camargo

Este trabalho desenvolve uma estratégia de controle preditivo de estados finitos baseado na Teoria da Potência Instantânea (teoria p-q) para compensação paralela de um sistema isolado de geração em um gerador de indução auto-excitado (GIAE), garantindo qualidade de energia através de regulação de tensão e compensação de harmônicos. Além disso, os sinais de referência do controlador são calculados a partir da potência ativa e reativa obtidas pela teoria p-q. O inversor empregado é topologia fonte de tensão de três pernas, que é conhecido como uma solução simples para essa aplicação. Como o inversor possui um número finito de estados de chaveamento possíveis, o FCS-MPC é o método escolhido para predizer o próximo estado que minimiza a função custo. Resultados de simulação são apresentados neste trabalho a fim de validar o sistema de controle proposto.

**Palavras-chave:** Teoria p-q. Controle Preditivo. GIAE. Compensação Harmônicos. Regulação de Tensão.

# ABSTRACT

## FINITE SET PREDICTIVE CONTROL BASED ON P-Q THEORY FOR VOLTAGE REGULATION AND HARMONIC COMPENSATION IN A OFF-GRID SEIG

AUTHOR: Marcos Vinicius Soares Gonçalves
ADVISOR: Robinson Figueiredo de Camargo

This work deals with a predictive finite set control together with the Instantaneous Power Theory (p-q theory) for parallel compensation of an distributed off-grid generation system based on a self-excited induction generator (SEIG), ensuring power quality through voltage regulation and harmonic compensation. Furthermore, the controller reference signals are calculated from active and reactive power obtained by the p-q theory, in order to perform an optimized control. The inverter employed is a three-leg voltage source inverter (VSI), which is a well known simple solution for this application. Since the inverter has a finite switching possibilities, a discontinuous control is chosen to predict the next switching state that minimizes the cost function, for that, a FS-MPC strategy is defined. Simulation results are presented in this work in order to validate the proposed control system.



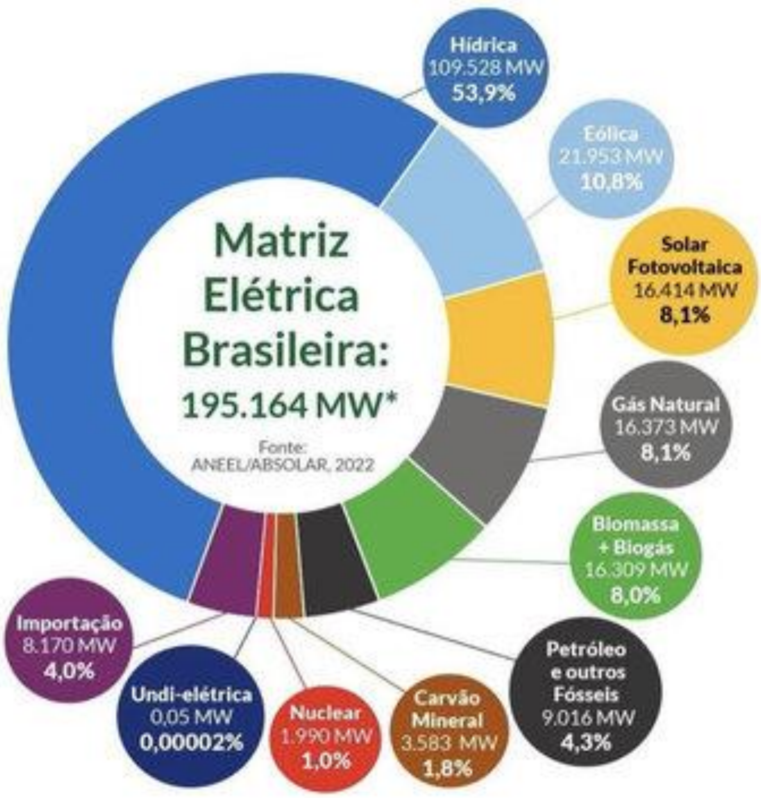
**Keywords:** p-q Theory Predictive control. SEIG. Harmonic compensation. Voltage regulation.

**SUMÁRIO**

## 1 INTRODUÇÃO

Nos dias de hoje existe um grande crescimento na demanda por energia, isso traz uma necessidade cada vez maior de melhorar a eficiência das nossas formas de geração de energia. As fontes de energia não renováveis são limitadas e causam danos ao meio ambiente. Tendo isso em vista as fontes de energia renováveis por não poluírem o meio ambiente e não serem um recurso finito como analisa A. S. Tomazini (2022), vem crescendo cada vez mais e se tornando uma parcela cada vez maior da matriz energética do mundo como mostra a Figura 1.

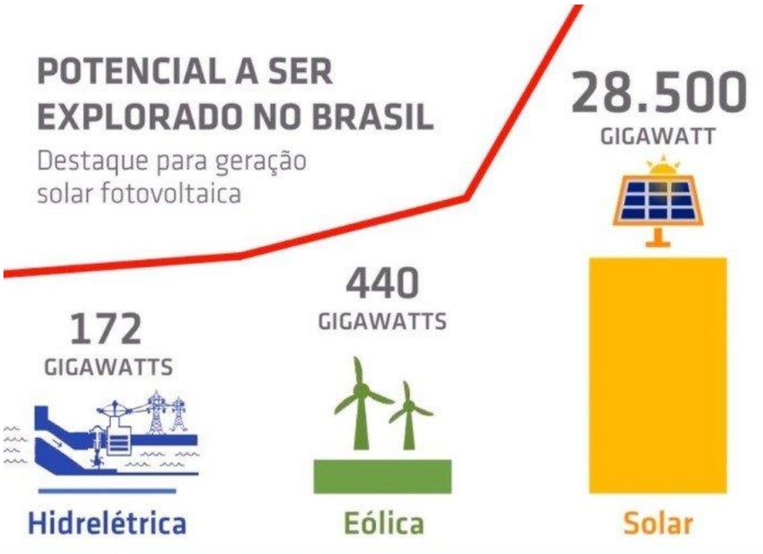
Figura 1 – Matriz energética brasileira




Fonte: (Conexão Tocantins et al., 2022).

No entanto, ainda existe um grande espaço para crescimento. Quando falamos de mercado de energia solar, estas e outras fontes de energia renovável vem sendo cada vez mais utilizadas no mundo de hoje como mostra a Figura 2.

Figura 2 – Potencial de energia a ser explorado




Fonte: (Portal-energia et al., 2018).

Diante do aumento na necessidade destes recursos, surge uma demanda de crescimento proporcional em busca de implementações destes sistemas, o gerador de indução auto-excitado é uma solução comumente encontrada na literatura para geração de energia com fontes renováveis devido a sua versatilidade, baixo custo e simples implementação (Ujjwal Kumar Kalla et al., 2020). Porém, junto a isso traz a necessidade de regulação de tensão e, quando necessária, compensação de componentes harmônicos para garantir uma qualidade no fornecimento de energia. Nesse contexto, este trabalho consiste na elaboração de uma estratégia de controle para garantir o funcionamento e confiabilidade destes sistemas de geração de energia quando são conectadas diferentes tipos de cargas. Alguns trabalhos similares foram desenvolvidos como G. M. Cocco et al., (2022) por exemplo.

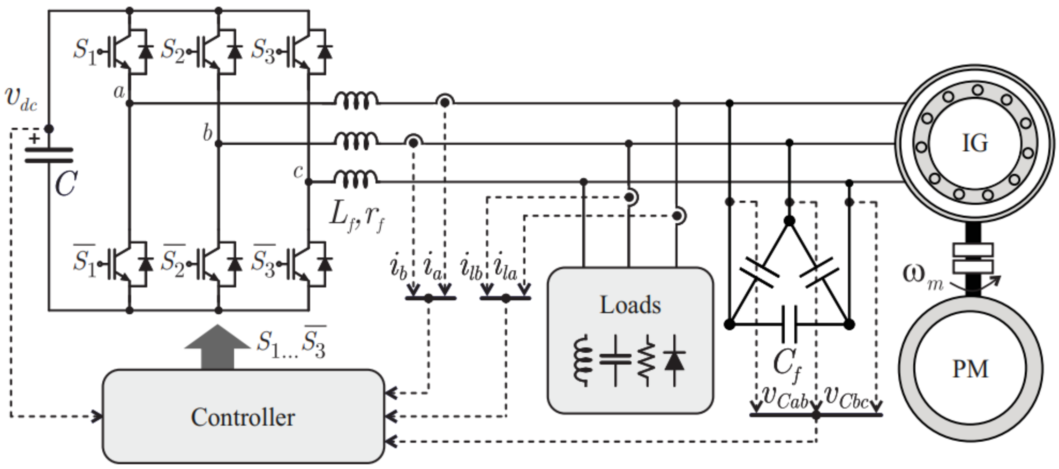
## 1.1 OBJETIVOS

Os objetivos deste trabalho são apresentar um sistema que através do uso da teoria p-q forneça as referências adequadas para que o controlador possa realizar a regulação e a compensação, desenvolver o algoritmo MPC e projetar os controladores escolhidos em tempo discreto. Realizar simulações para validar o controle desenvolvido.

## 2 DICUSSÃO

Este trabalho é apresentado ao decorrer dos capítulos em forma de um artigo previamente escrito, onde o mesmo tem enfoque no projeto, apresentando a topologia utilizada, modelagem do sistema, como funciona o método de controle. A Figura 3 ilustra o modelo de sistema utilizado.

Figura 3 – Modelo do sistema

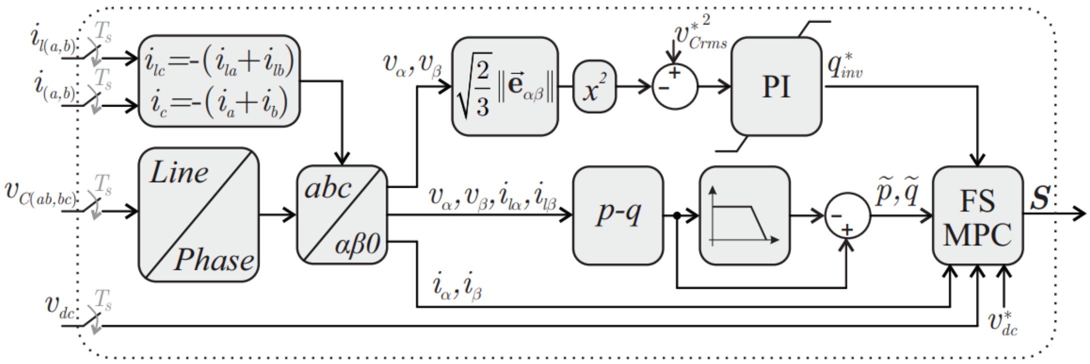



Fonte: (M. V. Gonçalves et al., 2022).

O modelo do sistema consiste em um gerador de indução conectado a um inversor fonte de tensão em paralelo que atua como compensador estático de reativos, a forma construtiva comum na literatura para este inversor é ser alimentado por um capacitor num barramento CC o qual controla a quantidade de potência ativa e reativa injetada pelo inversor no circuito. Um filtro passa-baixas é conectado na saída do inversor para retirar os harmônicos em alta frequência gerados pela comutação, além disso a parte capacitiva do filtro serve como excitação para o gerador. A carga é conectada em paralelo e sensores de corrente e tensão são utilizados para as medições dos sinais que serão levados ao controlador.

Em seguida é feita uma lógica de controle como mostrado na Figura 4, onde os sinais de entrada são a corrente de carga *il*, a corrente do inversor *i*, a tensão de linha V*c*, e a tensão no barramento CC *Vdc*. Primeiro é encontrada a terceira componente das variáveis de entrada pois é possível fazer isso num circuito a três fios, após isso os sinais são transformados para as coordenadas $\alpha\beta$. Para o funcionamento do gerador é necessário que seja fornecida uma parcela de potência reativa, esta é obtida do barramento CA, através do valor rms, e passando por um PI pois este tipo de controlador funciona bem com sinais contínuos no tempo. O sinal de entrada *Vdc* é levado junto a uma referência diretamente ao controlador pois é possível predizer o seu próximo estado. Os sinais de potência ativa e reativa gerados pela teoria p-q passam por um filtro passa-baixa para separar as partes alternadas das partes contínuas, as partes alternadas serão os sinais de referência para compensação no controlador. Assim uma lógica de controle é feita pelo MPC que encontra o próximo estado de chaveamento que melhor se encaixa para o circuito.

Figura 4 – Diagrama de blocos do sistema de controle




Fonte: (M. V. Gonçalves et al., 2022).

# 3 ARTIGO

Nesta seção é apresentado o artigo no qual este trabalho de conclusão de curso que segue o modelo para inclusão de artigo científico se baseia. O artigo “*p-q Theory Based Predictive Control for Voltage Regulation and Harmonic Compensation of Standalone SEIG*”. Este artigo foi submetido no 14 Seminar on Power Eletronics and Control no dia 20 de agosto de 2022 e está de acordo com as normas de submissão do congresso, além disso está formatado conforme o modelo de artigo para congressos IEEE, em língua inglesa para que seja incluso na biblioteca digital IEEE Xplore.

# $p$-$q$ Theory Based Predictive Control for Voltage Regulation and Harmonic Compensation of Standalone SEIG

***Abstract*—This paper deals with a predictive power control strategy using the Instantaneous Power Theory (*p-q* theory) for shunt compensation of an distributed off-grid generation system based on a self-excited induction generator (SEIG), ensuring power quality through voltage regulation and harmonic compensation. Furthermore, the controller reference signals are calculated from active and reactive power obtained by the *p-q* theory, in order to perform an optimized control. The inverter employed is a three-leg voltage source inverter (VSI), which is a well known simple solution for this application. Since the inverter has a finite switching possibilities, a discontinuous control is chosen to predict the next switching state that minimizes the cost function, for that, a FS-MPC strategy is defined. Simulation results are presented in this paper in order to validate the proposed compensation control system based on *p-q* theory.**

***Index Terms*—*p-q* theory, Predictive control, SEIG, Harmonic compensation, Voltage regulation.**

## I. Introduction

The world as we know it today is moved by electricity. The energy generation systems that utilize non renewable fuels are restricted, although the ones that use renewable sources, as like solar and wind, have an enormous growing capacity and less environmental damage. In global terms, wind and solar energy generation, nowadays, build up to ten per cent of the electricity consumed in the world [1]. This fact places an increasing importance on the renewable energetic solutions such as wind, solar, biomass and hydro power.

In isolated renewable generation systems the self-excited induction generator (SEIG) makes a good solution with low cost for hydro and wind power sources, although it presents voltage regulation problems when a load variation happens, furthermore, together with non linear loads, they drain harmonic currents, which makes these systems applications less attractive.

As presented in the literature, to solve the SEIG voltage regulation problems, a Voltage Source Inverter (VSI) as Distribution Synchronous Static Compensator (DSTATCOM) is used [2]. Generally, the papers use PI (Proportional Integral) type controllers [3] that consists in a simple control method, that works better with time continuous signals, others use PR (Proportional Resonant) [4], [5] which work better in terms of tracking alternating time signals, although the operation frequency must be defined and the controller wont be able to compensate signals in other frequencies unless the algorithm is rewritten, which in a case of disturbances in other frequency make the controller inefficient.

In this paper, will be studied the Model Predictive Control (MPC), among the main advantages of using the predictive controller, there is the controller capability to track and follow the reference signal variations and abrupt step in phase and amplitude [6], [7]. Current an voltage measures are normally use in this controllers to state prediction, in this paper the $p$-$q$ theory [8] will be the tool to generating the power references and analysing the benefits of using it together with the MPC.

As the energy control and conversion technologies advances, new construction models for the so called frequency inverters with voltage source topology, operating as a DSTATCOM used to voltage regulation and control coupled with many different systems [2]. Together with the SEIG, this inverter represents the system that will be studied in this paper.

Due to the SEIG features, in order that the voltage distortions remains as minimal as possible, it requires reactive power supply. Furthermore the nature of the loads that will be connected to the system must be taken into account. For managing a form of voltage regulation when connected in parallel with the SEIG, and for rectifying the current unbalances and harmonics caused by the loads, it makes a attractive implementation.

For the sake of the modeled system good performance, it is necessary to work with an adequate control technique in order to regulate the voltage. In this paper will be presented DSTATCOM controlled by MPC for voltage regulation and harmonic compensation of SEIG. The control strategy predicts the next optimal state over the inverter states, and uses a reference power to apply the necessary rectifications. This reference active and reactive power was calculated using the $p$-$q$ theory, simulation results where obtained to validate the proposed control technique and the method to calculate the references.

## II. System Modeling and Description

The system model proposed in this paper is present in Figure 1. In order to control the terminal voltages the SEIG needs an reactive power supply [9]. It is connected in parallel together with the DSTATCOM and the loads. Powered by the dc bus, the inverter injects currents in the system in order to regulate the SEIG currents.

To simplify the system modeling, the SEIG is represented as an equivalent of an voltage source in series with an inductor ($L_g$) [4], as shown in Figure 2.

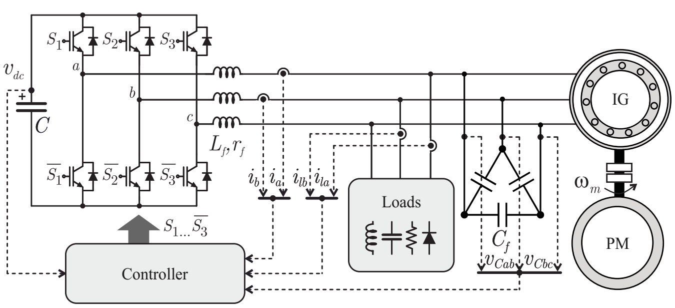



Fig. 1. Block diagram of the compensation system.

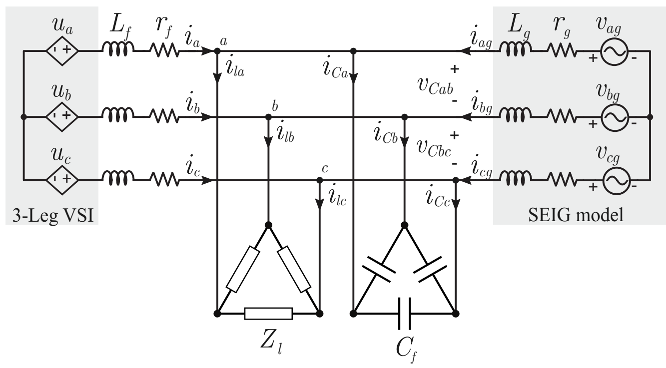



Fig. 2. Three-phase equivalent circuit.

From the model, the inverter currents and PCC voltages in *abc* reference frame can be written as:

$$\begin{bmatrix}\dot{i_a}\\ i_b\\ i_c\end{bmatrix}=\frac{r_f}{L_f}\mathbf{I}_{3\times3}\begin{bmatrix}i_a\\ i_b\\ i_c\end{bmatrix}+\frac{1}{3L_f}\begin{bmatrix}2&-1&-1\\-1&2&-1\\-1&-1&2\end{bmatrix}\begin{bmatrix}v_a-v_{Ca}\\ v_b-v_{Cb}\\ v_c-v_{Cc}\end{bmatrix}, \quad (1)$$

$$\begin{bmatrix}\dot{v_{Ca}}\\ v_{Cb}\\ v_{Cc}\end{bmatrix}=\frac{\mathbf{I}_{3\times3}}{C_f}\begin{bmatrix}i_a+i_{ag}-i_{la}\\ i_b+i_{bg}-i_{lb}\\ i_c+i_{cg}-i_{lc}\end{bmatrix}, \quad (2)$$

where $i_a, i_b$ e $i_c$ are the inverter currents, $r_f$ and $L_f$ are the output filter inductance and resistance, $v_a, v_b$ and $v_c$ are the inverter phase voltages, $v_{ca}, v_{cb}$ and $v_{cc}$ are the capacitor exciting voltages, $i_{ag}, i_{bg}$ and $i_{cg}$ are the SEIG output currents, $v_{ag}, v_{bg}$ e $v_{cg}$ are the SEIG voltages e $i_{la}$, $i_{lb}$ $i_{lc}$ are the load currents.

It is possible to obtain the uncoupled model of the voltage and current variables by observing the system in $\alpha\beta$ frame by means of power invariant Clarke transform written:

$$\begin{bmatrix}v_\alpha\\ v_\beta\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1&-\frac{1}{2}&-\frac{1}{2}\\0&\frac{\sqrt{3}}{2}&-\frac{\sqrt{3}}{2}\end{bmatrix}\begin{bmatrix}v_a\\ v_b\\ v_c\end{bmatrix}, \quad (3)$$

$$\begin{bmatrix}i_\alpha\\ i_\beta\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1&-\frac{1}{2}&-\frac{1}{2}\\0&\frac{\sqrt{3}}{2}&-\frac{\sqrt{3}}{2}\end{bmatrix}\begin{bmatrix}i_{la}\\ i_{lb}\\ i_{lc}\end{bmatrix}. \quad (4)$$

Then, from (1) and (2), the model can be expressed as:

$$\begin{bmatrix}\dot{i_\alpha}\\ i_\beta\end{bmatrix}=-\frac{r_f}{L_f}\mathbf{I}_{2\times2}\begin{bmatrix}i_\alpha\\ i_\beta\end{bmatrix}+\frac{\mathbf{I}_{2\times2}}{L_f}\begin{bmatrix}v_\alpha-v_{C\alpha}\\ v_\beta-v_{C\beta}\end{bmatrix}, \quad (5)$$

$$\begin{bmatrix}\dot{v_{C\alpha}}\\ v_{C\beta}\end{bmatrix}=\frac{\mathbf{I}_{2\times2}}{C_f}\begin{bmatrix}i_\alpha+i_{\alpha g}-i_l\alpha\\ i_\beta+i_{\beta_g}-i_l\beta\end{bmatrix}. \quad (6)$$

The dc bus and ac bus model can be found relating the active and reactive power through the dc and ac side capacitors by:

$$\frac{C}{2}\frac{dv_{dc}^2}{dt}=-P_{inv}=-\left(v_\alpha i_\alpha+v_\beta i_\beta\right), \quad (7)$$

$$\frac{C}{2}\frac{dv_{Crms}^2}{dt}=Q_{inv}+Q_g-Q_{load}. \quad (8)$$

In addition, the magnitude of $\alpha\beta$ voltage vector can be related to PCC voltages rms value, according to [8] it can be given by:

$$\vec{\mathbf{e}}_{\alpha\beta}=v_\alpha+jv_\beta, \quad (9)$$

$$v_{Crms}=\sqrt{\frac{2}{3}}\left\|\vec{\mathbf{e}}_{\alpha\beta}\right\|. \quad (10)$$

Making in this way, is possible to apply PI controllers for the ac. Although in the dc bus, since all the variables are being measured, its possible to model and predict the $v_{dc}(k+1)$ and so, it is directly carried to the MPC cost function.

## III. Control Strategy

With the modeling done, it is possible to choose the control strategy that has the best fitting to the system. The proposed control presented in Figure 3 is projected to compensate the harmonics and reactive caused by connecting the load to the SEIG. So it is necessary to supply a reference to compensate the generator currents [10]. The compensation will be done by injecting active and reactive power from the inverter. Using the *p-q* theory is possible to find the compensation active power ($p$) and the reactive power ($q$) by:

$$p=v_\alpha i_{l\alpha}+v_\beta i_{l\beta}, \quad (11)$$

$$q=v_\beta i_{l\alpha}-v_\alpha i_{l\beta}. \quad (12)$$

Note that there are two portions $\overline{p}$ and $\tilde{p}$ being respectively part continuous and part alternate which together are the signal $p$. Furthermore there is $\overline{q}$ and $\tilde{q}$ as part continuous and part alternate of $q$. So, its possible to show mathematically the real and imaginary powers:

$$p=\overline{p}+\tilde{p}, \quad (13)$$

$$q=\overline{q}+\tilde{q}. \quad (14)$$

The alternate portions $\tilde{p}$ e $\tilde{q}$ are the amount of power that can represent unbalance or harmonics brought along by some types of loads [8]. Therefore the alternate portions of this signal must be compensated. For that it is necessary to separate the alternate and the continuous portion using a first order low pass filter (LPF) given by:

$$G_{\mathrm{LPF}}(s)=\frac{\omega}{s+\omega}. \quad (15)$$

Having separated the alternate portions of $p$ and $q$, the control methods were defined. The system will work with an

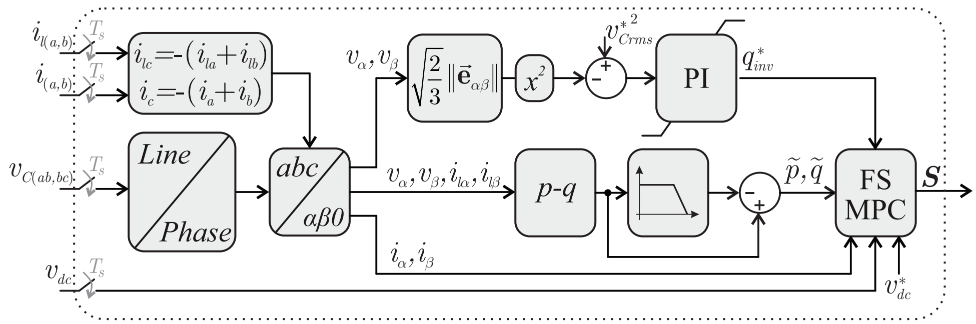



Fig. 3. Block diagram of proposed control system.

outer and an inner loop. The first consisting in regulate the PCC voltages, and the other to control the inverter currents by means of a discontinuous control method (MPC). Due to the loop differences, different control methods were used. The dc bus, is directly solved to the MPC. The rms value of the ac is extracted and then it goes in a PI controller, it generates then a reactive power reference signal $q_{inv}^{*}$ that goes into the MPC cost function.

Because of its simplicity and efficiency with continuous signals, the PI controller was chosen for voltage regulation in the ac [3]. Considering the reactive powers of the load and the generator, a Proportional-integral controller can be used to provide control of the PCC voltages. The controller expression in the discrete time domain is given by:

$$\begin{aligned} q_{inv}^{*}(k) &= k_i x_{pi}(k) + k_p e_v(k); \\ x_{pi}(k+1) &= x_{pi}(k) + T_s e_v(k), \end{aligned} \tag{16}$$

Where $k_p$ and $k_i$ are respectively the proportional and integral gain of the PI, and $e_{v(k)} = v_{Crms}^{*2}(k) - v_{Crms}^{2}(k)$ is the outer loop voltages errors.

Due to its capability to track reference signals and its abrupt variations, and follow variations in any frequencies for its non linear characteristic the predictive control method was chosen [6]. It can be applied in two ways, Finite Control Set Model Predictive Control (FCS MPC) and Continuous Control Set Model Predictive Control (CCS MPC). Due to characterization of the system of this paper the FCS MPC is the an attractive option, because of its digital nature, since the inverter by having three legs can only have eight possible switching states, together with that the FCS MPC has a lot of eases of use [11].

The proposed control system does not need the use of any positive sequence tracking phase locked loops or Kalman filter based algorithms to inverter synchronization [12]. Once the references are calculated using $\alpha\beta$ transformations and *p-q* theory concepts, the discontinuous control performed by the MPC has the ability to quickly track nonlinear references.

Since it is a three-leg inverter it switching states can be represented by the Table I. The VSI is able to synthesize a voltage vector found with the Clarke Power Invariant Transformation for each switching state [9].

TABLE I
SWITCHING STATES AND OUTPUT VOLTAGES.

| **Vector** | **Switching State** | **Output Voltages** |
|---|---|---|
| $j$ | $S = [S_1\ S_2\ S_3]$ | $\mathbf{u}_{\alpha\beta} = [v_\alpha\ \ v_\beta]$ |
| 1 | [0 0 0] | [0 0] |
| 2 | [0 0 1] | $\left[-\sqrt{1/6}\quad -1/\sqrt{2}\right]$ |
| 3 | [0 1 0] | $\left[-\sqrt{1/6}\quad 1/\sqrt{2}\right]$ |
| 4 | [0 1 1] | $\left[-\sqrt{2/3}\quad 0\right]$ |
| 5 | [1 0 0] | $\left[\sqrt{2/3}\quad 0\right]$ |
| 6 | [1 0 1] | $\left[\sqrt{1/6}\quad -1/\sqrt{2}\right]$ |
| 7 | [1 1 0] | $\left[-\sqrt{1/6}\quad 1/\sqrt{2}\right]$ |
| 8 | [1 1 1] | [0 0] |

$$\mathbf{i}_{\alpha\beta}(k+1) = \left[\mathbf{I}_{2\times2} + \mathbf{A}T_s\right]\mathbf{i}_{\alpha\beta}(k) + \mathbf{B}T_s\left[\mathbf{u}_{\alpha\beta}(k) - \mathbf{v}_{\alpha\beta}(k)\right]. \tag{17}$$

$$\mathbf{v}_{\alpha\beta}(k+1) = \mathbf{I}_{2\times2}\mathbf{v}_{\alpha\beta}(k) - \frac{\mathbf{I}_{2\times2}}{C_f}T_s\mathbf{i}_{l\alpha\beta}(k) + \frac{\mathbf{I}_{2\times2}}{C_f}T_s\mathbf{i}_{\alpha\beta}(k). \tag{18}$$

With I being the identity matrix, Ts is the switching period, $\mathbf{i}_{\alpha\beta}(k+1)$ the predicted inverter currents array for $(k+1)$, $\mathbf{v}_{\alpha\beta}(k+1)$ the predicted voltage array for $(k+1)$ and $v$ being the bus voltage array in each switching state.

In order to find the predicted dc-link voltage, the first thing is calculating $v_{dc}(k+1)$ with:

$$v_{dc}^2(k+1) = v_{dc}^2(k) - \frac{2}{C}T_s\left(v_\alpha(k)i_\alpha(k) + v_\beta(k)i_\beta(k)\right). \tag{19}$$

Knowing that the controller acts with a time delay, it has to work compensating the variables state to $(k+1)$ [13]. The switching period $Ts$ is fixed, due to the fact that using a modulator allows to settle the switching frequency, this way even if the algorithm finishes the next step prediction, it waits the end of the switching cycle to make the control act.

**Algorithm 1:** Control algorithm

Sampling $\mathbf{i}_{\alpha\beta}(k), \mathbf{v}_{\alpha\beta}(k), \mathbf{i}_{l\alpha\beta}(k), v_{dc}(k)$;
$\mathbf{i}_{\alpha\beta}(k+1), \mathbf{v}_{\alpha\beta}(k+1), v_{dc}(k+1) \leftarrow f_p\{\mathbf{x}(k), \mathbf{S}(k)\}$;
$g_{min} \leftarrow \infty$;
**for** each $j$ from 1 to 8 **do**
  $\mathbf{i}^p_{\alpha\beta} \leftarrow f_p\{\mathbf{i}_{\alpha\beta}(k+1), \mathbf{S}_j\}$;
  $\mathbf{v}^p_{\alpha\beta} \leftarrow f_p\left\{\mathbf{v}_{\alpha\beta}(k+1), \mathbf{i}^p_{\alpha\beta}\right\}$;
  $v^p_{dc} \leftarrow f_p\left\{v_{dc}(k+1), \mathbf{i}^p_{\alpha\beta}, \mathbf{v}^p_{\alpha\beta}\right\}$;
  $p^p_{inv}, q^p_{inv} \leftarrow f_{p-q}\left\{\mathbf{i}^p_{\alpha\beta}, \mathbf{v}^p_{\alpha\beta}\right\}$;
  $g_j = f_g\{\tilde{p}, \tilde{q}, q^*_{inv}, v^*_{dc}, p^p_{inv}, q^p_{inv}, v^p_{dc}\}$;
  **if** $g_j < g_{min}$ **then**
    $g_{min} \leftarrow g_i$;
    $j_{otm} \leftarrow j$;
  **end**
**end**
$\mathbf{S}(k+1) \leftarrow \mathbf{S}_{j_{otm}}$;

Where the compensation powers are found by:

$$p^p_{inv} = v^p_\alpha i^p_\alpha + v^p_\beta i^p_\beta, \tag{20}$$

$$q^p_{inv} = v^p_\beta i^p_\alpha - v^p_\alpha i^p_\beta. \tag{21}$$

Next this variables are insert in the cost function, that execute a compensation through mathematical operations trying to minimize the difference between the error signal and the compensation signal sent to the system. The inverter switching state that minimizes the equation results is the next state chose by the controller. The cost function is:

$$g_j = (\tilde{p} - p^p_{inv})^2 + (\tilde{q} + q^*_{inv} - q^p_{inv})^2 + \lambda\left(v^{*2}_{dc} - v^{p2}_{dc}\right)^2, \tag{22}$$

Where $\lambda$ is the weight factor chosen to ensure good performance for the dc bus voltage. $\tilde{p}$ and $\tilde{q}$ are the alternate portions of load active and reactive power that will be compensated, $q^*_{inv}$ is the inverter power and $p^p_{inv}$ and $q^p_{inv}$ are the inverter predicted powers.

## IV. Results

Simulation results obtained using matlab are shown in this section, in order to show this topology good functioning. For that, the SEIG and VSI simulation parameters are shown, respectively, in Table I and II. In order to test the control capability of tracking and following the reference signal, several tests were made and the results are shown in the following graphics.

The step responses of the dc bus and the ac bus voltages are shown respectively in Figure 4 and 5. It is possible to note the controller capability to follow the signals steps in the transitory, and keep a good track in the steady-state.

Figure 6 show the system variables response in several transient load changes. Figure 6(a) presentes the $p$ and $q$ load powers responses to different types of load variations. The inverter active and reactive power are shown in Figure 6(b) and (c) respectively, presenting the response to the different load changes and the signals wave form as well as the control tracking capability in the transient and steady-state. The dc bus continuous voltage signal and the ac rms signal tracking response are shown in Figure 6(d). In Figure 6(d) the dc-link voltage waves are presented. The system line voltages are shown in Figure 6(e). In Figure 6(f) the SEIG currents are shown. Figure 6(g) show the currents sent by the inverter. And Figure 6(h) presents the load currents.

A part of this paper objectives is to minimize the harmonics generated by distortions in the system cause by load changes, for that the PCC voltages total harmonic distortion (THD), SEIG currents total demand distortion (TDD) and their harmonic content is measured and shown in Figure 7. For comparison purposes, the harmonic content of the variables is also shown without the compensation of the inverter con-

TABLE II
SEIG PARAMETERS

| Parameter | Value |
|---|---|
| Nominal Power | $P_n = 3.7$ kW (5 cv) |
| Line Voltage | $V_C = 220$ V (rms) |
| Rotating Speed | $n = 1730$ rpm |
| Frequency | $f = 60$ Hz |
| Excitation Capacitor | $C_f = 40$ µF |
| SEIG Equivalent | $L_g = 5$ mH, $R_g = 0.2\ \Omega$ |

TABLE III
VSI PARAMETERS

| Parameter | Value |
|---|---|
| Output Filter | $L_f = 2.5$ mH, $R_f = 0.1\ \Omega$ |
| Dc-link Capacitor | $C = 4700$ µF |
| Switching Period | $Ts = 20$ µs |

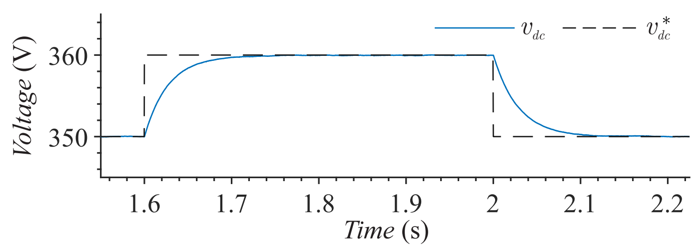



Fig. 4. Step response for the dc-link voltage.

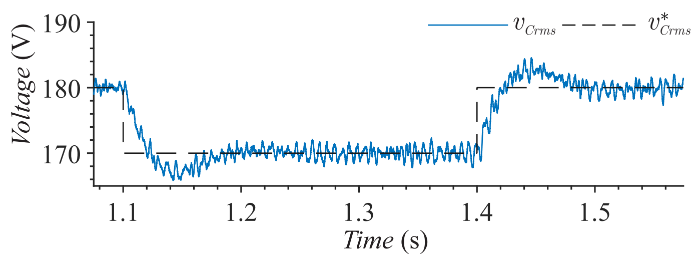



Fig. 5. Step response for the PCC voltages.

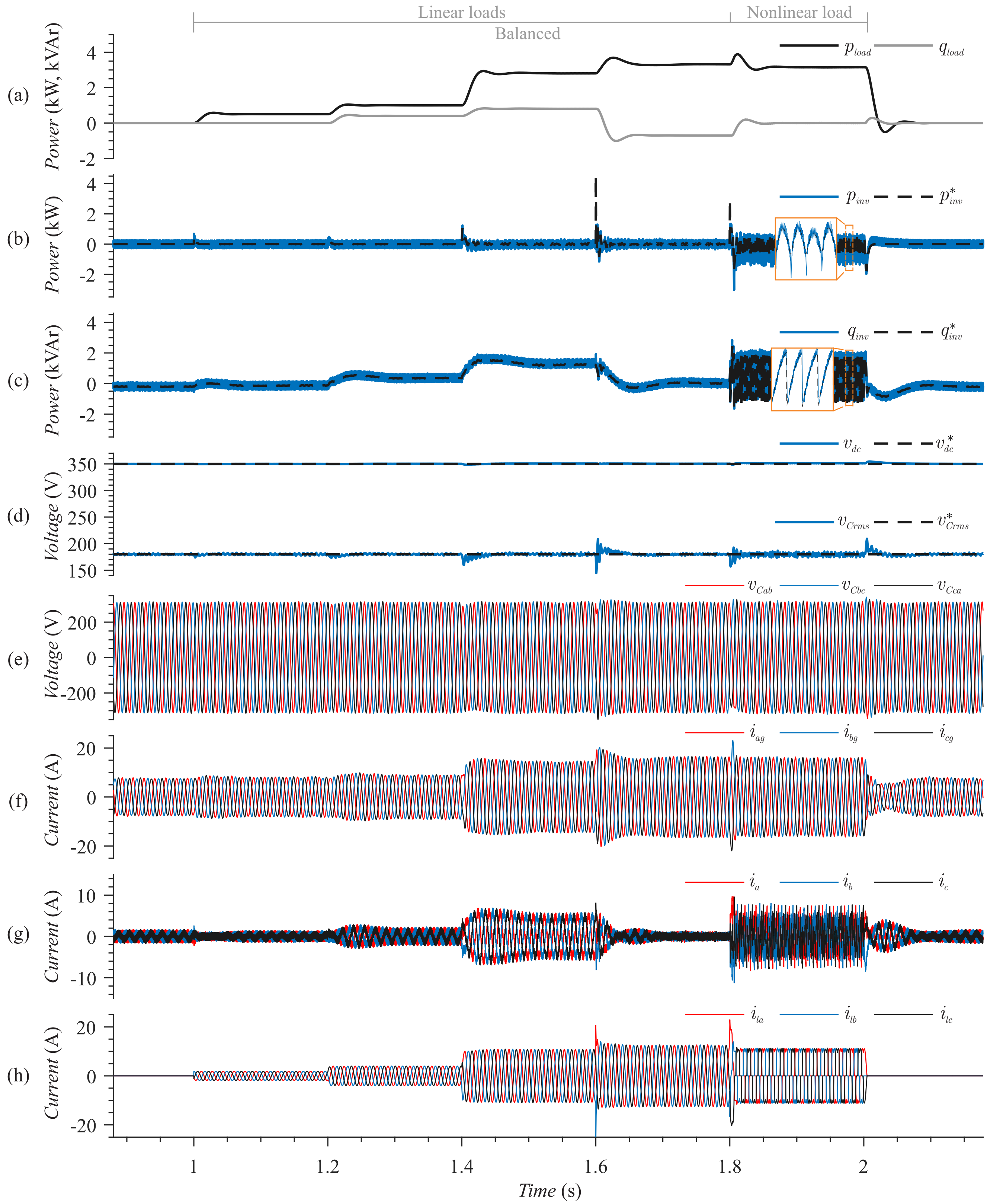



Fig. 6. Response of the system to transient load changes: (a) active ($P$) and reactive ($Q$) power of load connected to PCC; (b) active ($P$) and (c) and reactive ($Q$) power processed by the inverter; (d) dc bus voltage and PCC rms voltage; (e) Line voltages; (f) SEIG currents; (g) Inverter currents; (h) Load currents.

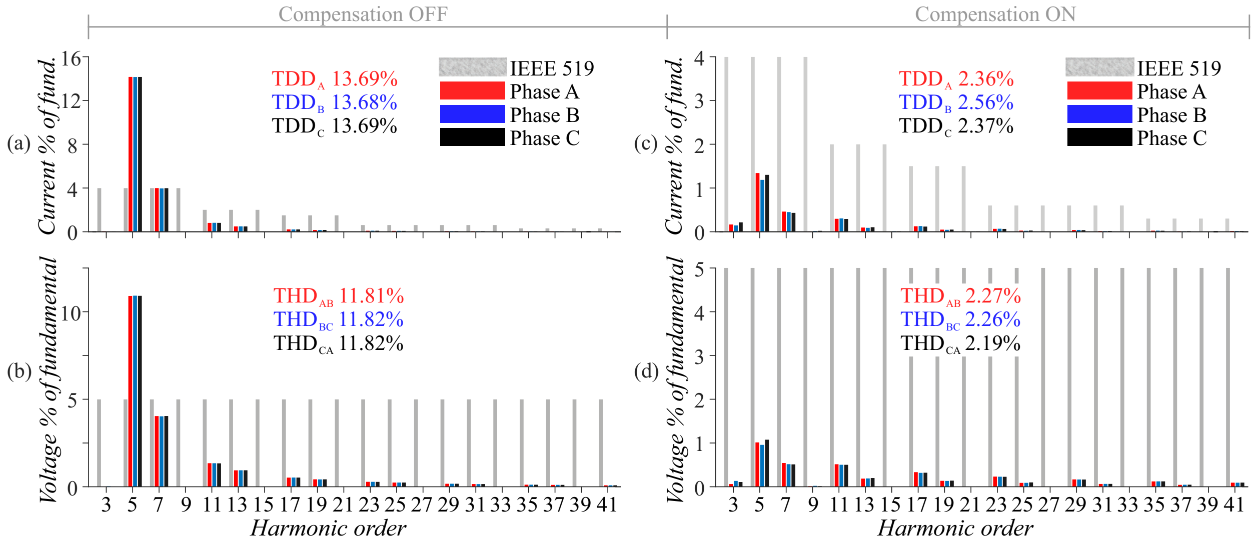



Fig. 7. Harmonic content under 3.2 kW nonlinear load: (a) Uncompensated SEIG currents; (b) Uncompensated PCC voltages; (c) Compensated SEIG currents; (d) Compensated PCC voltages.

trol system. It is possible to note that even with nonlinear loads connected to PCC, the system is able to maintain the harmonics lower than the maximum level recommended by IEEE 519 standard. On the other hand, the uncompensated system presents a bad performance in terms of power quality, exceeding the limits of THD (8%) and TDD (5%) in addition to some individual harmonics.

## V. Conclusion

This paper presents the development of a predictive control strategy together with a reference generation technique that uses *p*-*q* theory for harmonics compensation and voltage regulation. Using the $p$ and $q$ powers to calculate the cost function. The proposed strategies are validated by the simulation results presented in this paper, showing a good response to system and load variations. By analysing the THD it is possible to notice a reduction in the system harmonics, those that are according to IEEE 519-2014 standards for harmonics.

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# 4 CONCLUSÃO

Esse trabalho apresentou o projeto desenvolvido para controle, regulação de tensão e compensação de harmônicos de um sistema de geração de energia. Todos os resultados de simulação foram obtidos através da plataforma Matlab.

Os resultados obtidos se mostraram confiáveis e dentro das normas da IEEE, apresentando uma melhora na eficiência do sistema como um todo. Além disso, comprova a eficiência da utilização da teoria p-q para geração das referências e método do controle preditivo através de compensação por potência. Este trabalho contribui para acelerar o desenvolvimento de sistemas de geração de energia e novas topologias para os mesmos. Diferentes tipos de estratégias de controle além do controle preditivo, diferentes tipos de filtro além do passa-baixa, diferentes métodos de geração de referência e também diferentes formas construtivas no sistema são algumas oportunidades para desenvolvimento de trabalhos futuros a partir desta topologia.

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