

## Current predictive controller for high frequency resonant inverter in induction heating

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### ABSTRACT

In the context of this article, we are particularly interested in the modeling and control of an induction heating system powered by high frequency resonance inverter. The proposed control scheme comprises a current loop and a PLL circuit. This latter is an electronic assembly for slaving the instantaneous phase of output on the instantaneous input phase, and is used to follow the rapid variations of the frequency. To further improve the transient dynamics of the studied system and in order to reduce the impact of measurement noise on the control signal, a generalized predictive control has been proposed to control the current of the inductor. We discussed the main steps of this command, whose it uses a minimization algorithm to obtain an optimal control signals, its advantages are: its design is simple, less complexity and direct manipulation of the control signal. The results have shown the effectiveness of the proposed method, especially in the parameters variation and/or the change of the reference current.

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## 1. INTRODUCTION

In induction heating, the control of current and consequently the power needs more and more of an advanced control technique to ensure a good regulation with precision, quickness and efficiency. Several classical methods of control have been adopted to control the frequency, current and power transmitted into the piece to be heated, whose [1-4] have successively proposed the use of PI and I regulators for induction heating applications. But these conventional control laws may be insufficient because they are not robust, especially when the accuracy requirements and other dynamic features of the system are stringent. An optimal regulator (LQR) has been proposed by [5] and [6], this method is not robust to the uncertainties of the models (uncertainties about the parameters, disturbances ....) [5], and [7] has also proposed the application of sliding mode control in serie-parallel LCC resonators for induction heating.

To have a better control of the coil current and to improve the performance of the controlled system, we propose in this work the technique of generalized predictive control (GPC) [8-12]. The proposed control method uses a minimization algorithm to obtain an optimal control signals. It is simple to design and implement compared to the conventional control method in terms of dynamic response and execution time. The proposed control method has several advantages such as less computational complexity, simpler controller design, direct manipulation of the control signal resulting in variable switching frequency and a faster dynamic response [8, 9].

The main contribution of this paper is the implementation of a high-performance current predictive control law for induction heating application, suitable for controlling a high frequency resonant mode inverters with as objective improve the slaving of the current which depends directly on temperature required for heating. This control strategy is used to develop a GPC control technique based on the prediction of the load current to generate the switching states of the inverter and consequently the supply voltages of the inductor. So, this contribution is a performance evaluation obtained through analyses and simulation.

The paper is organized as follows: firstly, the controlled system inductor-load associate with resonance high frequency inverter selected is modeled. Secondly, we discussed predictive control strategies. Thirdly, the application of the resulting predictive control of induction heating system is provided, of which we have regulated the current of the inductor which is in direct relation with the temperature of the piece to be heated at its desired value. Finally, the numerical simulation of the global system is presented with related results and comments.

**2. PROPOSED RESONANCE HF INVERTER**

The system of induction heating contain essentially: high frequency inverter, one or more inductors, and regulation of power transmitted to the load [13-15]. It is usual to represent induction heating system by electrical circuit equivalent to the inductor-piece to be heated, with equivalent resistor in series or parallel with equivalent inductance [16-20]. Whose:  $R_{eq}=R_c+R_i$ ;  $L_{eq}=L_c+L_i$ , With:  $R_c, L_c$  are Load resistor and inductance &  $R_i, L_i$  are Inductor resistor and inductance, and:  $R_{eq}, L_{eq}$ : equivalent resistor and inductance [19]. In the resonance converters, a capacitor is added to the circuit [21], it is exploited to minimize the electrical constraints on the switches, to maximize the transferred power and to reduce the harmonics [21-25]. Figure 1 shows resonant HF inverter and control stratdgy in IH.

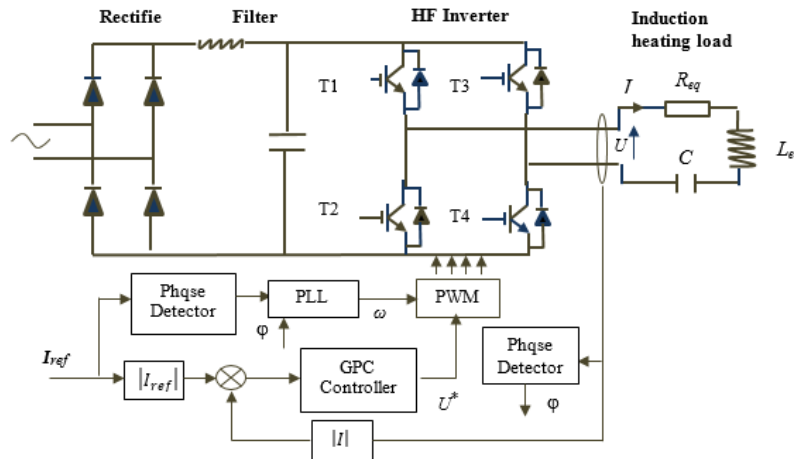


Figure 1. Resonant HF inverter with RLC series-resonant

**2.1. Modeling of the series-resonant inductor-load**

The equivalent equation of the resonant electrical circuit is as follows [20]:

$$U = (R_{eq} + j\omega L_{eq}) I + U_c \tag{1}$$

Or by state space [17]:

$$\dot{x} = Ax + Bu \quad \begin{cases} \frac{dI}{dt} = \frac{1}{L_{eq}}(U - R_{eq}I - U_c) \\ \frac{dU_c}{dt} = \frac{1}{C}I \end{cases} \tag{2}$$

whose:

$$x = \begin{pmatrix} I \\ U_c \end{pmatrix}, u = (U), A = \begin{pmatrix} -\frac{R_{eq}}{L_{eq}} & -\frac{1}{L_{eq}} \\ \frac{1}{C} & 0 \end{pmatrix}, B = \begin{pmatrix} \frac{1}{L_{eq}} \\ 0 \end{pmatrix}$$

Capacitor and inductor forms a resonant frequency which can be expressed as [24]:

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

**2.2. PWM control strategy for the proposed inverter**

The proposed control strategy consists of two loops: a current regulation loop and a frequency loop (PLL) Phase-locked-loop [26]. The PLL circuit is used to monitor rapid changes of system frequency during the induction heating process, it consists of a current sensor, a zero crossing detector, a low-pass filter and a voltage controlled oscillator (VCO). The VCO delivers a periodic signal whose amplitude is constant and whose frequency is proportional to the DC voltage applied to its input [27].

The current loop is based on the comparison of the output signal of the controller  $U^*$  with a variable frequency sawtooth signal. This frequency is generated by the PLL command. The difference between the two signals is applied to the input of a comparator providing a pulse train. In this article, we rely on the synthesis of an advanced current regulator.

**3. CURRENT GENERALIZED PREDICTIVE CONTROL**

The principle of this technique is to use a process model inside the current controller in real time to anticipate the future behavior of the process [8, 9, 12]. The objective of the predictive control strategy is twofold [10]:

- a. To estimate the future output of the plant by a linear predictor;
- b. To minimize a cost function based on the error between the predicted outputs, the reference trajectory and the future control error increment;
- c. At time  $k$ , solve an open loop optimal control problem over a predefined horizon and apply the first input;
- d. At time  $k+1$  repeat the same procedure. (The previous optimal solution is discarded).

**3.1. Prediction model**

The numerical prediction model is classically defined by the input / output transfer function. In generalized predictive control, the model is represented as CARIMA form (Controlled Auto-Regressive Integrated Moving Average) [11].

$$A(z^{-1})y(k) = B(z^{-1})u(k - 1) + \frac{C(z^{-1})\xi(k)}{\Delta(z^{-1})} \tag{4}$$

With,  $A(z^{-1})$ : the model input,  $B(z^{-1})$ : the model output,  $\xi(k)$ : white noise centered,  $z^{-1}$ : the delay operator,  $\Delta(z^{-1}) = 1 - z^{-1}$ : ensures integral action in the corrector, and  $A(z^{-1})$ ,  $B(z^{-1})$  et  $C(z^{-1})$ : polynomials defined by:

$$A(z^{-1}) = 1 + a_1z^{-1} + \dots + a_{na}z^{-na}$$

$$B(z^{-1}) = b_0 + b_1z^{-1} + \dots + b_{nb}z^{-nb}$$

$$C(z^{-1}) = 1 + c_1z^{-1} + \dots + c_{nc}z^{-nc}$$

This CARIMA model is represented by the Figure 2.

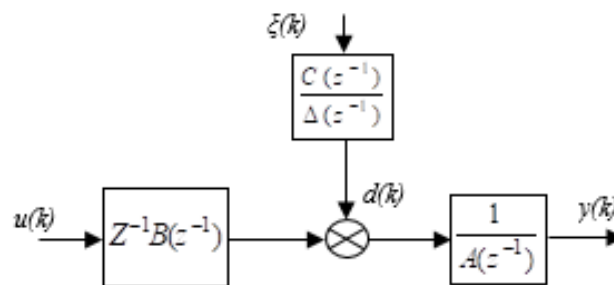


Figure 2. CARIMA prediction model

The optimal control signal can be achieved with the following algorithm [10]:  
 The previous iteration, after the minimization procedure at time k-1, gives the control vector:

$$u = [u(k - 1), u(k), \dots, u(k + N_u - 2)]^T$$

In the first iteration, the input vector control will contain some initial values provided by the user. The number of values presented must be equal to the control horizon.

1. The predictors of orders between  $N_1$  and  $N_2$  are calculated using the vectors  $u(k+N_1-1)$ ,  $y(k + N_1-1)$  and  $u(k+N_2-1)$ ,  $y(k+N_2-1)$ .
2. Minimizing the cost function  $J$  with respect to the control vector develops the optimal control signal:  
 $u = [u(k), u(k + 1), \dots, u(k + N_u - 1)]^T$

**3.2. Structure of the optimal predictor**

The calculation of  $y(k+j)$ , requires the solution of two Diophantine Fions, based on the model mentioned in (6). The j-step ahead predictor can be taken as follows [11]:

$$y(k + j/k) = \frac{F_j(z^{-1})}{C(z^{-1})} y(k) + \frac{H_j(z^{-1})}{C(z^{-1})} \Delta u(k - 1) + G_j(z^{-1}) \Delta u(k + j - 1) \tag{5}$$

Where:  $\Delta T_{em}(k + j) = 0$  for  $j \geq N_u$

The predicted output  $y(k+j)$  is decomposed in a conventional manner in free and forced response:

$$\frac{F_j(z^{-1})}{C(z^{-1})} y(k) + \frac{H_j(z^{-1})}{C(z^{-1})} \Delta u(k - 1) : \text{free answer}$$

$$G_j(z^{-1}) \Delta u(k + j - 1) : \text{forced answer}$$

where  $F_j$ ,  $G_j$  and  $H_j$  are the unique solution of the following Diophantine equations:

$$\Delta(z^{-1})A(z^{-1})J_j(z^{-1}) + z^{-1}F_j(z^{-1}) = C(z^{-1}) \tag{6}$$

$$C(z^{-1})G_j(z^{-1}) + z^{-1}H_j(z^{-1}) = B(z^{-1})J_j(z^{-1}) \tag{7}$$

**3.3. Matrix form of the prediction equation**

To simplify the notations, it is possible to use this matrix representation of the predictor in (5).

$$\hat{y} = G\tilde{u} + \frac{1}{C(z^{-1})} Fy(k) + \frac{1}{C(z^{-1})} H\Delta u(k - 1) \tag{8}$$

with:

$$F = \begin{bmatrix} F_{N_1}(z^{-1}) \\ \vdots \\ F_{N_2}(z^{-1}) \end{bmatrix}, H = \begin{bmatrix} H_{N_1}(z^{-1}) \\ \vdots \\ H_{N_2}(z^{-1}) \end{bmatrix} \text{ and } \tilde{u} = \begin{bmatrix} \Delta u(k) \\ \vdots \\ \Delta u(k + N_u - 1) \end{bmatrix},$$

$$w_{ref} = \begin{bmatrix} w_{ref}(k + N_1) \\ \vdots \\ w_{ref}(k + N_2) \end{bmatrix}, \hat{y} = \begin{bmatrix} \hat{y}(k + N_1) \\ \vdots \\ \hat{y}(k + N_2) \end{bmatrix} \text{ and } G = \begin{bmatrix} g_{N_1}^{N_1} & g_{N_1-1}^{N_1} & \dots & 0 \\ g_{N_1+1}^{N_1+1} & g_{N_1}^{N_1+1} & \dots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ g_{N_2}^{N_2} & g_{N_2-1}^{N_2} & \dots & g_{N_2-N_u+1}^{N_2} \end{bmatrix} \tag{9}$$

**3.4. Minimization of the criterion for the elaboration of the control law**

**3.4.1. Cost function**

The GPC control law is obtained by minimizing a finite-horizon quadratic criterion on future errors with a weighting term on the command [10]:

$$J = \sum_{j=N_1}^{N_2} [\hat{y}(j + 1) - w_{ref}(j + 1)]^2 + \lambda \sum_{j=0}^{N_u-1} [\Delta u(k + 1)]^2 \tag{10}$$

where :

$N_1$  : Minimum prediction horizon

$N_2$  : Maximum prediction horizon

$N_u$  : Control Horizon

$\lambda$  : Weighing factor

$w_{ref}(k)$  : Reference trajectory

$\hat{y}$  : Predicted output

$\Delta u$  : Increment control signal

With additional conditions:  $\Delta u(k+i-1) = 0, N_1 \leq N_u < i$

The matrix form of the criterion (10) is:

$$J_{GPC}(\tilde{u}) = M^T M + \lambda \tilde{u}^T \tilde{u} \quad (11)$$

with:

$$M = G\tilde{u} + \frac{1}{c(z^{-1})}Fy(k) + \frac{1}{c(z^{-1})}H\Delta u(k-1) - w_{ref} \quad (12)$$

The control action (13) is obtained by analytical minimization  $\frac{\partial J}{\partial \tilde{u}} = 0$  of the criterion (11):

$$\tilde{u}_{opt} = -N \left[ \frac{1}{c(z^{-1})}Fy(k) + \frac{1}{c(z^{-1})}H\Delta u(k-1) - w_{ref} \right] \quad (13)$$

where

$$N = [G^T G + \lambda I_{N_u}]^{-1} G^T = \begin{bmatrix} n_1^T \\ \vdots \\ n_{N_u}^T \end{bmatrix} \text{ and } \tilde{u}_{opt} = \begin{bmatrix} \Delta u(k)_{opt} \\ \vdots \\ \Delta u(k + N_u - 1)_{opt} \end{bmatrix}$$

In generalized predictive control GPC, only the first value of the sequence, the (14) is applied to the system, according to the principle of the receding horizon [9-12]:

$$u_{opt} = u_{opt}(k-1) - n_1^T \left[ \frac{1}{c(z^{-1})}Fy(k) + \frac{1}{c(z^{-1})}H\Delta u(k-1) - w_{ref} \right] \quad (14)$$

#### 4. SYNTHESIS OF THE PREDICTIVE CONTROL LAW

The construction of the predictive control laws requires a numerical prediction model of the system, the numerical model used for inductor-load with compensation capacitor according to Table 1 is represented by a continuous transfer function between the voltage  $U$  and the current  $I$ :

Table 1. Inductor-load parameters

$R_{eq}(\Omega)$	$L_{eq}(H)$	$C(F)$	$f_c(Hz)$
0.033	25.95e-6	420e-6	1525

$$T(s) = \frac{I}{U} = \frac{C p}{L_{eq} C p^2 + R_{eq} C p + 1} = \frac{0.42e-3 p}{10.9e-7 p^2 + 1.38e-5 p + 1} \quad (15)$$

The discretization of (15) (for one period of sampling of  $T_s = 10^{-3}$  sec) gives the model:

$$\frac{B(z^{-1})}{A(z^{-1})} = \frac{-0.2827 z^{-1} + 2827 z^{-2}}{1 + 1.05 z^{-1} + 0.2804 z^{-2}} \quad (16)$$

Where the polynomials  $(z^{-1})$ ,  $B(z^{-1})$  and  $C(z^{-1})$  in the CARIMA model (4) are:

$$\begin{cases} A(z^{-1}) = 1 + 1.05 z^{-1} + 0.2804 z^{-2} \\ B(z^{-1}) = -0.2827 z^{-1} + 2827 z^{-2} \\ C(z^{-1}) = 1 \end{cases}$$

The prediction (9) becomes:

$$\hat{I} = G\tilde{U} + F I(k) + H\Delta\tilde{U}(k-1) \quad (17)$$

where:

$$\hat{I} = \begin{bmatrix} \hat{I}(k+N_1) \\ \vdots \\ \hat{I}(k+N_2) \end{bmatrix}, \tilde{U} = \begin{bmatrix} \Delta U(k) \\ \vdots \\ \Delta U(k+N_u-1) \end{bmatrix}$$

With:

$$F(q^{-1}) = \begin{bmatrix} F_1(q^{-1}) \\ \vdots \\ F_j(q^{-1}) \end{bmatrix}; H(q^{-1}) = \begin{bmatrix} H_1(q^{-1}) \\ \vdots \\ H_j(q^{-1}) \end{bmatrix} \text{ and } G = \begin{bmatrix} g_1 & 0 & 0 & 0 \\ g_2 & g_1 & 0 & 0 \\ \vdots & \dots & g_1 & 0 \\ g_j & \dots & g_2 & g_1 \end{bmatrix}$$

The prediction (17) for  $j = 1$  is:

$$\hat{I}(k+1) = G_1(z^{-1})\Delta\tilde{U}(k) + F_1(z^{-1})I(k) + H_1(z^{-1})\Delta U(k-1) \quad (18)$$

where:

$$\begin{aligned} G_1(z^{-1}) &= g_1 = -0.2827 \\ F_1(z^{-1}) &= -0.0500 + 0.7696z^{-1} + 0.2804z^{-2} \\ H_1(z^{-1}) &= 2827 \end{aligned}$$

The analytic minimization  $\frac{dJ_{\text{GPC}}}{d\tilde{U}} = 0$  gives the future control signal (19):

$$U_{opt} = U_{opt}(k-1) - n_1^T [F(z^{-1})I(k) + H(z^{-1})\Delta U(k-1) - I_{ref}] \quad (19)$$

For  $N_1 = 1, N_u = 3, N_2 = 3$  and  $\lambda = 0.01$ :

$$n_1^T = [-0.0000 \quad 0.3537 \quad 0.0000],$$

$$F(z^{-1}) = \begin{bmatrix} -0.0500 + 0.7696z^{-1} + 0.2804z^{-2} \\ 0.7721 + 0.2419z^{-1} - 0.0140z^{-2} \\ 0.2033 + 0.5802z^{-1} + 0.2165z^{-2} \end{bmatrix}$$

$$H = \begin{bmatrix} 2827 \\ -141.3500 \\ 2.1827e + 03 \end{bmatrix}$$

## 5. SIMULATION AND RESULTS

The inductor-load as shown in Figure 3 with the parameters shown in Table 1, is controlled by the current loop being conceived around the GPC control to generate the switching states of the inverter and consequently the supply voltages of the inductor. Simulations and the tests carried out were focused around this current loop.

### 5.1. Discussion

The choice of settings parameters  $N_1 = 1, N_u = 1, N_2 = 25$  and  $\lambda = 0.01$ , leads to stable and well-cushioned behavior (Figure 4). The sampling period is 0.001second ( $k=10^{-3}$  s), and we work in an interval of  $k = [0 \ 500]$ , which corresponds to  $t = [0 \ 0.5\text{s}]$ , which confirms the accuracy and speed of

the trajectory follow-up, with response time equal to  $5k = 0.005s$  without overshoot as shown in Figure 4. Carefully modify the control setting parameters as shown in Figure 5, give us acceptable results with a reduced response time, no overshoot and good reference tracking. For sinusoidal signals as shown in Figure 6 and Figure 7, the current is superimposed on its reference even with variation of the reference current amplitude.

**5.2. Robustness test**

Figure 8 to Figure 11 respectively show the behavior of the system with its regulation by the predictive control with an increase of the resistance of the inductor-load assembly of 75% of its nominal value, and decrease of the inductance by 75% da nominal values at the instant  $40k = 0.04s$ . The simulations results show clearly the insensitivity of the predictive control to the variation of the resistance and the inductance. We can notice a little disturbance at the instant  $40k$ , then the current returns to its desired trajectory.

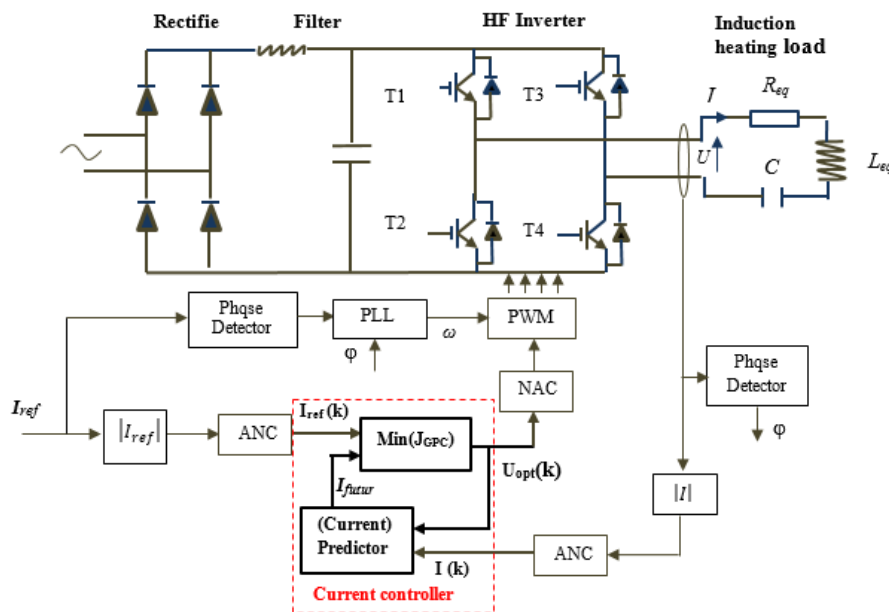


Figure 3. Global Diagram of the induction heating controlled by GPC

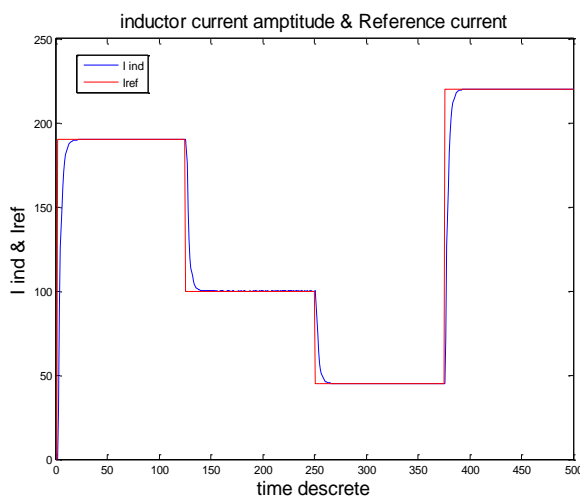


Figure 4. Inductor current and its reference

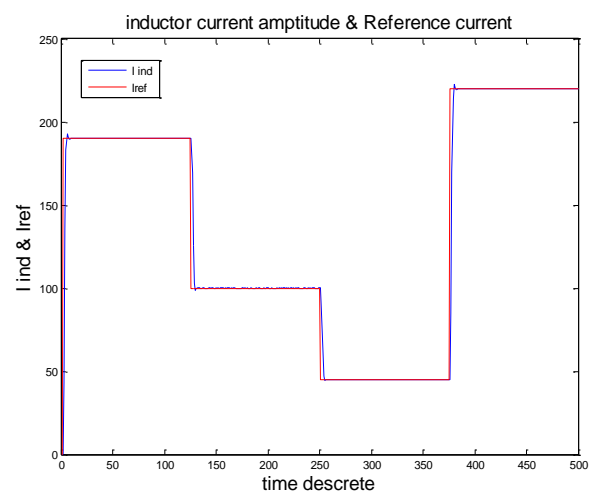


Figure 5. Response for  $N1=1, N2=27, Nu=1, \lambda=0.01$

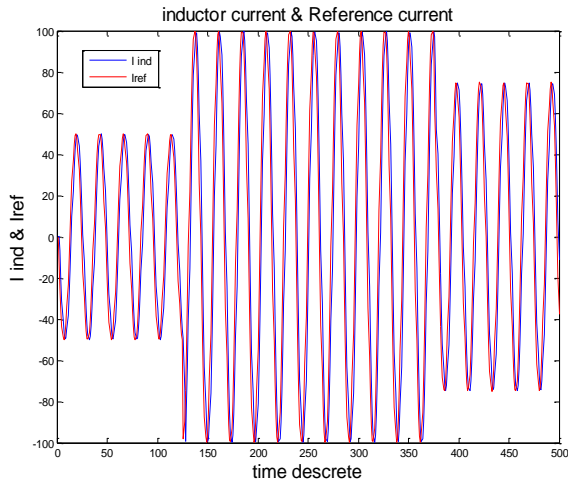


Figure 6. Harmonic response of current in [0 500k]

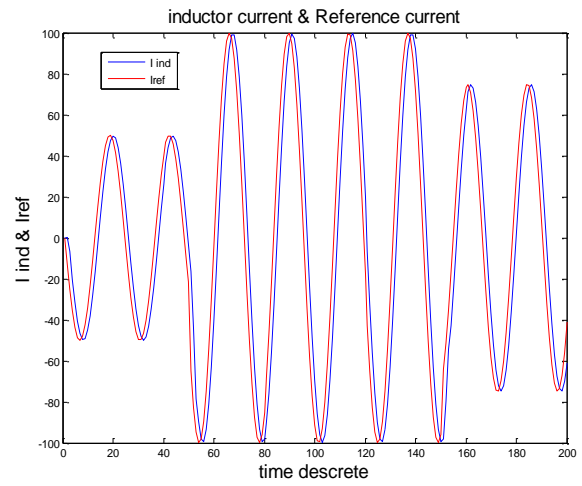


Figure 7. Harmonic response of current in [0 200k]

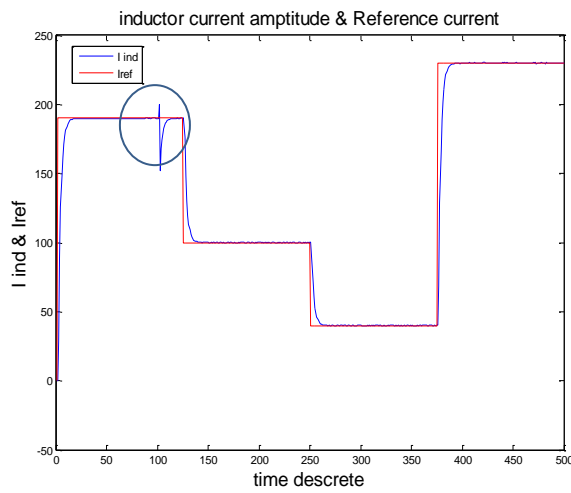


Figure 8. Robustness test; increasing of +75% Req

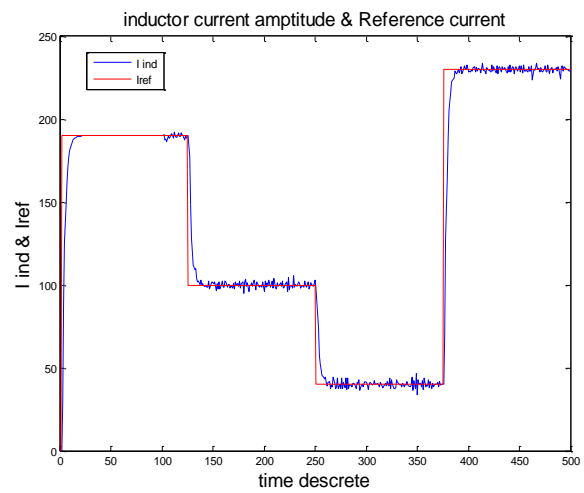


Figure 9. Robustness test; decreasing of -75% Leq

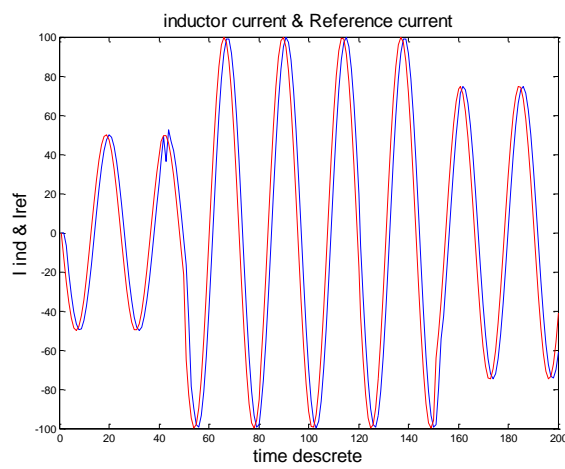


Figure 10. Robustness test; increasing of +75% Req

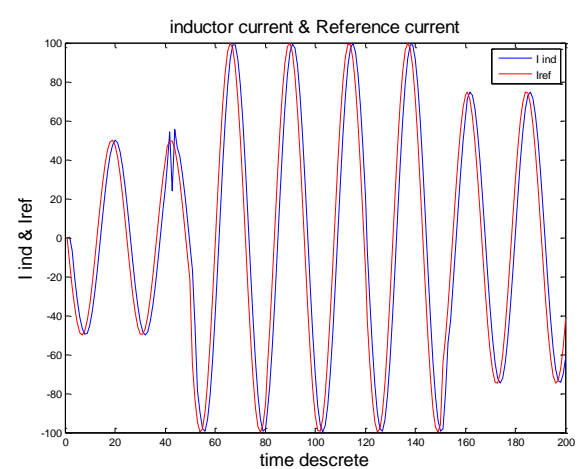


Figure 11. Robustness test; decreasing of -75% Leq



## 6. CONCLUSION

The present work has allowed us to see the modeling and control of high-frequency supply systems (HF inverter) of induction heating, where we have presented the strategy of the predictive control, the central idea and the interest of this article. All these concepts are detailed in the specific framework of the generalized predictive control (GPC). This method gives very satisfactory results and well during a reference variation than during a presence of disturbance.

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