Using Genetic Algorithm to Tune PI-Controllers for the Direct-Drive Synchronous Wind Generators

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Abstract—**This paper presents a novel methodology** for **tuning proportional-integral (PI) controllers gains for the grid-side converter of direct-drive synchronous wind generator using a genetic algorithm (GA) approach. The control approach aims to improve the behavior of the direct-current (DC)-link voltage, by a more effective contribution of direct-drive wind generator controllers to the system controllability when an electrical fault occurs. The time-domain simulations are carried out using the single-machine infinite bus system model with one direct-drive synchronous generator. The performance of the wind generator with optimized controller parameters and with the parameters designed by the pole placement technique are compared to demonstrate that the control performance of the system with optimized controller parameters permits the improvement of the converter ride-through capability.**

Keywords-Direct-dive synchronous generator; wind turbine; genetic algorithm; PI-controllers; static power converter.

I. INTRODUCTION

The greater necessity of investments on renewable energy resources as an approach to contribute to the reduction of the green-house gases emission on the planet has been favoring the formation of new regulations and government incentives that aim to stimulate the exploration of these resources by independent producers, as well as by electrical public utilities. As effect, it has been verified during the last years a significant growth of wind parks all around the world, evolving, mainly, technologies with electronic interface of static converters, amongst these ones it is highlighted the direct-drive synchronous wind generator (DDSWG).

The widespread integration of these wind generators on the electrical systems, taking into account its seasonal characteristics of operation, has promoted changes on the usual structure of the electrical grids so that the system operators have been defining procedures aiming, mainly, to guarantee the power system stability and protection. Currently, most of the grid requirements addresses low voltage ride-through (LVRT) and grid support capabilities of the wind turbines due to the short-circuits or other contingencies. In those specific cases, the machine must be connected to the grid, which means that its terminal voltage must remain with a voltage profile defined by the operator during the grid faults. Different voltage characteristic curves have been used in many European countries and worldwide in accordance to the rules of electrical system operation of each country [1]-[3].

Due to this fact, various control techniques that explore the electronic interface of the wind generators have been presented on the literature of this area. In [4], for example, the converter connected to the grid injects reactive power during the fault so that the voltage on the terminals of a doubly fed induction generator does not overcome the minimum limit imposed by the voltage curve established by the grid operator. Similar procedure is presented in [5], where the converter connected to the grid injects a certain current so that the reactive power increases, thus reducing the terminal voltage falls during the fault by this method.

However, besides the control strategies that aim to attend the requisite of LVRT, there is the necessity to adopt a specific control to the direct current (DC)-link voltage, when this voltage suffers significant oscillations because of the imbalance of currents on the dc-link during the grid short-circuits or other faults. In the particular case of the DDSWG, this kind of control is even more essential because the converter connection is in the output of the generator that is on the stator of the machine and then suffers directly the impact caused by those faults on the grid. With an objective of reducing the DC-link voltage oscillations and consequently to avoid a possible out of service of the wind generator produced by the action of the protection of the electronic converters, the use of a chopper is discussed in [6], which is the control that allows to reduce the imbalance on the DC-link current.

In this paper, the DC-link voltage control is accomplished by the converter connected to the grid, exploring a strategy of current control on coordinates d-q, which will be described in detail in topic II. On the basis of this methodology, the control loops are defined so that the controller's PI gains can be obtained using the pole placement method [7]. An important contribution of this work is on the fact that these gains will be used as reference to the definition of the search space of the GA that aims to find the gains that optimize the DC-link voltage behavior during faults. Specifically, the system will be submitted to the worst kind of the contingency on the electrical system, which is a short-circuit applied on the grid.

II. DIRECT-DRIVE SYNCHRONOUS WIND GENERATOR (DDSWG) MODEL

A simplified diagram of the direct-drive model used in this article is depicted in Figure 1. The prototype presents a conventional synchronous generator, with a voltage regulator connected in series with the AC-DC-AC electronic converters that operates on a pulse-width modulation (PWM) strategy.

The converter connected to the generator (PWM-C1) has the objective of controlling the active and reactive powers of the electrical machine. In this case, the active power is adjusted by the mode control, following the reference signal of the active power that comes from the characteristic power curve of the wind turbine, according to what is shown in Figure 1. The reactive power is adjusted to zero, aiming to reduce the internal losses of the machine, when this power is not injected to the electrical circuit due to the connection of the converters on the generator output.

In addition, the converter connected to the electrical grid (PWM-C2) controls the dc-link voltage and the quadrature current i_q that is injected on the AC grid. It is to be referred that on both the converters C1 and C2, a vectorial control strategy on coordinate d-q is used, where direct v_d and quadrature v_q axis voltages control signals are generated by PI controllers. This methodology makes possible an appropriate decoupling between the control loops [8]. Besides the AC-DC-AC electronic converters, the wind generator presents a pitch control to regulate its speed according to a curve of maximum power extraction. With this, the wind turbine tends to operate with the maximum power for a certain wind speed.

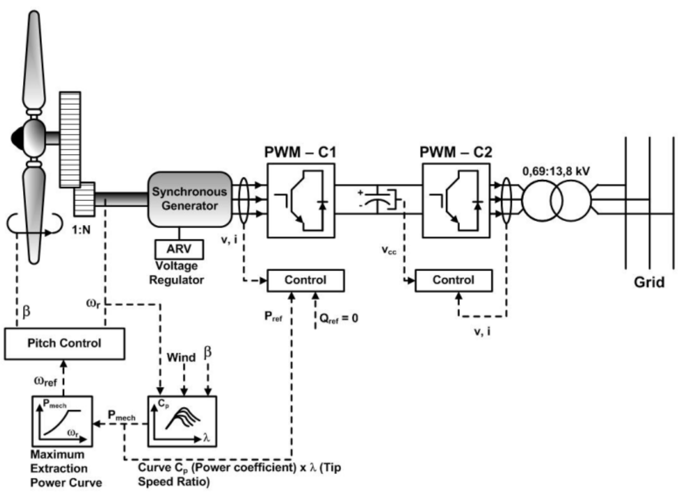

Figure 1. Simplefied diagram of the DDSWG

III. THE CONTROL LOOPS OF THE DDSWG

A. Current-Control Loops of Grid-Side Converter

To define the transfer functions of the control loops in converter C2, the circuit illustrated in Figure 2 was used. From Figure 2, the following voltage equations are obtained to the direct and quadrature axis [9]:

$$
\begin{aligned}
e_d &= R_t i_d + L_t \frac{di_d}{dt} + v_d - \omega L_t i_q \\
e_q &= R_t i_q + L_t \frac{di_q}{dt} + v_q + \omega L_t i_d
\end{aligned}
\tag{1}
$$

where e_d and e_q are the direct and quadrature voltages on the electrical grid, respectively; v_d and v_q means the direct and quadrature voltages of the converters, respectively; R_t and L_t correspond to the resistance and the inductance of the transformer that connects the converter to the grid, respectively; and ω consists of the angular speed of the electrical grid.

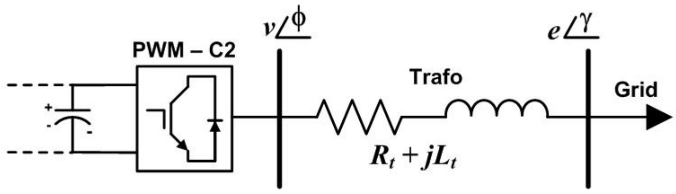

Figure 2. Circuit of the grid-side converter

According to equation (1), the currents i_d and i_q injected by C2 converter into the grid can be regulated from the converter voltages v_d and v_q. Following this, it is possible to rewrite equations (1) as:

$$
\begin{aligned}
R_t i_d + L_t \frac{di_d}{dt} &= e_d - v_d + \omega L_t i_q = v_{dt} \\
R_t i_q + L_t \frac{di_q}{dt} &= e_q - v_q - \omega L_t i_d = v_{qt}
\end{aligned}
\tag{2}
$$

By applying the Laplace transform in (2), the following functions related to the currents and the direct and quadrature voltages are obtained as:

$$
\begin{aligned}
I_d(s) &= G(s) V_{dt}(s) \\
I_q(s) &= G(s) V_{qt}(s)
\end{aligned}
\tag{3}
$$

Where $G(s) = \dfrac{1}{L_t s + R_t}$.

From (3), the current control loops are defined as shown in Figure 3. The PI controllers generate the control signals v_{dref} and v_{qref} in a way to regulate the currents i_d and i_q, respectively. These signals are then synthesized by the converter and, so, injected in the electrical grid. It is assumed that there are no delays and so the converter transfer function

G_{conv} may be considered ideal because $v_{dref} = v_d$ and $v_{qref} = v_q$.

It is verified that the elements of voltage compensation from the grid (e_d and e_q) that are present on the loops i_d and i_q make it possible a better decoupling between both loops by the fact that they compensate the influence of the coupling elements $\omega L_t i_q$ and $\omega L_t i_d$.

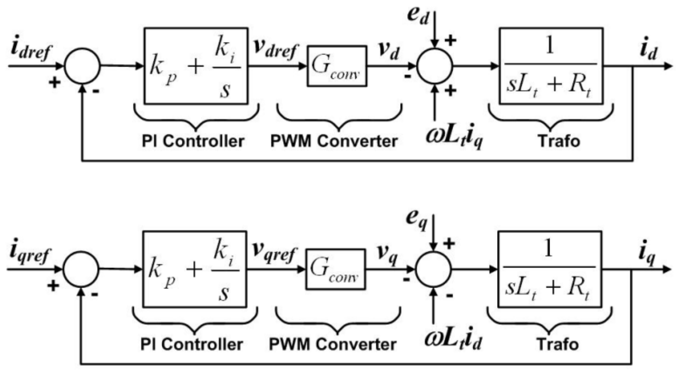

Figure 3. Current-control loops of grid-side converter

B. *DC-link Voltage-Control Loop of Grid-Side Converter*

Because the current i_q of converter C2 will be maintained equal to zero by the control, the active power at the input of C2 becomes approximately proportional to the current i_d . As the behavior of the DC-link voltage depends effectively on the active power control loop for the DC-link voltage, it can be dimensioned to regulate the current i_d that the converter injects into the grid. In Figure 4, the currents flowing on the DC-link are observed, so that:

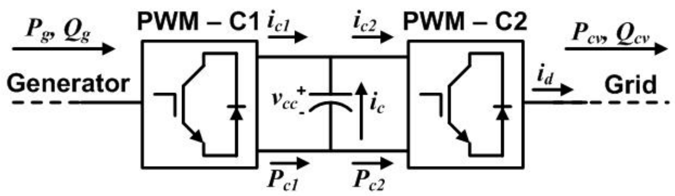

Figure 4. Machine-side and grid-side converters

$$i_c = i_{c2} - i_{c1} \quad \Rightarrow \quad C\frac{dv_{cc}}{dt} = i_{c2} - i_{c1}$$

By neglecting losses on the converters, the input and output active powers on converter C2 can be defined as

$$P_{c2} = P_{cv} \quad \Rightarrow \quad i_{c2} v_{cc} = v_d i_d \quad \Rightarrow \quad \frac{i_{c2}}{i_d} = \frac{v_d}{v_{cc}} \tag{5}$$

From equation (5), the transfer function between the voltage and the capacitor current is defined as:

$$\frac{V_{cc}(s)}{I_c(s)} = \frac{1}{sC} \quad \Rightarrow \quad V_{cc}(s) = \frac{1}{sC} I_c(s) \tag{6}$$

Where,

$$V_{cc}(s) = \frac{1}{sC}\left[I_{c2}(s) - I_{c1}(s)\right]$$

Thus, the block diagram to the calculation of the DC voltage can be defined as shown in Figure 5.

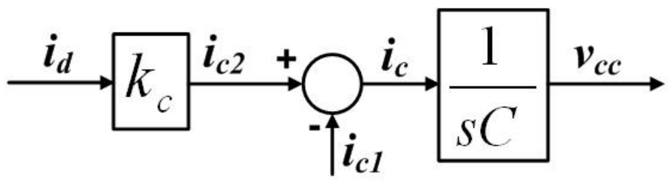

Figure 5. Block diagram of the DC-link voltage

In Figure 5, $k_c = \frac{v_d}{v_{cc}}$ basically corresponds to a current gain provided by the converter, relating currents i_d and i_{c2} , respectively. It is also observed that if current i_d is regulated, voltage v_{cc} can be controlled. By this method, the closed loop control of the DC voltage can be finally defined as illustrated in Figure 6.

In Figure 6, current i_{c1} can be considered as a perturbation; hence, it does not take part on the project of the controller's gains. In addition, the internal current loop can be considered as ideal for presenting a very fast dynamics. In the case of k_c , it is observed that this gain depends on the voltage v_d that varies on time by the fact that it is controlled by C2 to regulate current i_d (verify Figure 3). So the gain k_c is variable on time for each operation point of the DDWG. Nevertheless, assuming to the controller PI project $v_{cc} = 1$ p.u. and $v_d = 1$ p.u. referred on the bases voltages (appendix) used to the AC and DC sides of converter C2, respectively, the gain $k_c = 1$ is obtained. On the basis of these assumptions, the closed loop transfer function of Figure 6 corresponds to the following equation:

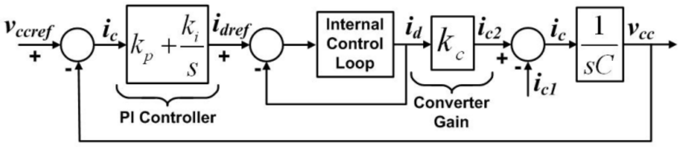

Figure 6. DC-link voltage control loop

IV. POLE PLACEMENT CONTROLLER DESIGN

The pole placement technique is a formal methodology to design proportional-integral-derivative (PID) controllers that is based on the knowledge of the plant transfer function. The objective of the method is to design controllers that will result in specified poles for the closed-loop transfer function. In this paper, the pole placement technique is used to obtain the gains for the machine-side and grid-side converters of the DDSWG, but it will be presented in detail only in the design procedure for the grid-side converter.

For the calculation of the controllers' gains using the poles placement procedure, it is necessary to define the bandwidths for the control loops, which are dependent on the converter's switching frequency and are used as performance indicators of the control actions. The controller design by the pole placement technique usually produces a robust and very efficient controller.

A. Grid-Side Converter Current Controller

Considering that the control loops of currents i_d and i_q are similar, it may be assumed to them the following open loop $G_o(s)$ and closed loop $G_c(s)$ transfer functions:

$$G_o(s) = \frac{k_p s + k_i}{s(L_t s + R_t)} \tag{7}$$

$$G_c(s) = \frac{k_p s + k_i}{L_t s^2 + (R_t + k_p)s + k_i} \tag{8}$$

Where k_p and k_i are the proportional and integral gains of the PI controller, respectively. The closed loop poles can be obtained through the right choice of the controller gains k_p and k_i. These poles are then defined by putting the equation denominator equal to zero in (7), resulting in the following characteristic equation [10]:

$$L_t s^2 + (R_t + k_p)s + k_i = 0 \tag{9}$$

Knowing that a 2nd order system is characterized by the characteristic equation:

$$s^2 + 2\xi\omega_n s + \omega_n^2 = 0 \tag{10}$$

Where ξ and ω_n correspond to the damping ratio and the natural frequency of the system oscillation, respectively. Then, the gains k_p and k_i can be obtained by equating equations (9) and (10), so that:

$$\omega_n^2 = \frac{k_i}{L_t} \quad \Rightarrow \quad k_i = L_t\omega_n^2 \tag{11}$$

$$2\xi\omega_n = \frac{R_t + k_p}{L_t} \quad \Rightarrow \quad k_p = 2\xi\omega_n L_t - R_t \tag{12}$$

ω_n and ξ can be established by the settling time t_s and the maximum overshoot M_p used in the controller project. In this article, the assumed project criteria were $t_s \le 4s$ and $M_p \le 20\%$ [7]. $M_p = e^{-\frac{\pi\xi}{\sqrt{1-\xi^2}}} = 20\%$ corresponds to $\xi_{\min} = 0{,}456$ and to $t_s = \frac{4}{\xi\omega_n} = 4$, then, ξω=400Hz is obtained in which $\omega_n = 2{,}1929$ rad/s.

Substituting ω_n and ξ on (11) and (12), respectively, neglecting the resistance R_t and considering $L_t = X_t = 6{,}6667$ p.u., being X_t the transformer reactance in p.u. (refer to appendix), the following is obtained:

$k_p = 13{,}3328$ e $k_i = 32{,}0588$.

To complete the control project of the converter C2 by taking into account the previously defined loop currents, the following project for the dc-link control loop is presented.

B. DC-link Voltage Controller

$$G_c(s) = \frac{k_p s + k_i}{Cs^2 + k_p s + k_i} \tag{13}$$

(4)

Where the characteristic equation is defined as:

$$s^2 + \frac{k_p}{C}s + \frac{k_i}{C} = 0 \tag{14}$$

From the poles and zeros allocation method, described on topic B, it is obtained:

$$k_p = 2\xi\omega_n C \quad \text{e} \quad k_i = C\omega_n^2 \tag{15}$$

Considering the same project criteria presented on topic B, that is, $t_s \le 4s$ and $M_p \le 20\%$, which results $\xi_{\min} = 0{,}456$ and $\omega_n = 2{,}1929$ rad/s, being the capacitor $C = 0{,}004$ p.u. (refer to appendix), the values of the gains are:

$$k_p = 0{,}008 \quad \text{e} \quad k_i = 0{,}0192$$

The PI gains are calculated, considering that the DC-link voltage control loop cut-off frequencies are ten times smaller than the cut-off frequency of the current control loop.

Figure 7 shows the time response of the closed loop transfer function to a step input in the DC voltage, using the project parameters obtained so far. It is observed that the overshoot and the settling time are above the established values to the project. To fix this problem, the gain k_p was readjusted to 0,015, obtaining a satisfactory result, as shown in figure 7.

On the basis of the obtained gains for all the PI controllers by the poles and zeros allocation method, the use of genetic algorithm (GA) to find new gains that optimize the response of the DC voltage and i_q control loops, respectively, is presented in the following.

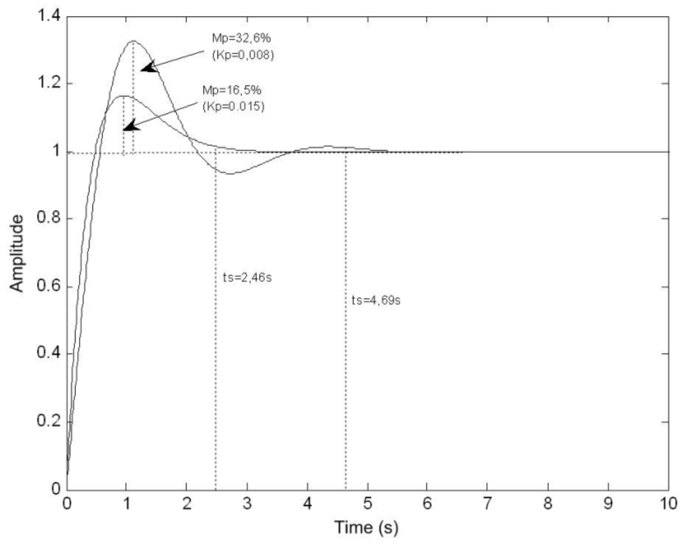

Figure 7. Time response of the closed loop transfer function to a step input in the DC-link voltage

V. GA-MULTI OBJECTIVE OPTIMAL CONTROL

Genetic algorithms are search algorithms formulated on the Natural Selection Theory. First, they are based on the generation of a population formed by a random group of individuals that can be considered as possible solutions for a certain problem. During the evolutionary process, this population is evaluated, and for each individual, it is associated an evaluation grade that matches its adaptation ability in a certain environment. A percentage of the most adapted ones is maintained, whereas the others are dismissed. The ones maintained by the selection operator suffer modifications on their characteristics through mutation and crossing generating descendents to the next generation. This process is repeated until a satisfactory solution is found.

Besides being a very elegant strategy by the fact that it is based on the genetic evolution, the GA´s are able to identify and explore environmental factors and converge to optimum or nearly optimum solutions in a great variety of problems because they do not impose many of the limitations found on traditional search methods [11].

To use the GA as a tool to solve a certain problem, it is necessary to represent the problem in a way that the GA can work properly on it. In this article, the main objective of the GA consists on finding the PI controllers' gains of the control loops associated with converter C2 aiming to optimize, in particular, the DC voltage behavior of the AC-DC-AC link of the wind generator during the occurrence of short-circuits on the electrical grid. That is, from a refined tuning of the controller's gains, it is possible to reduce the DC voltage oscillations in consequence of the current imbalance between the DC and AC sides of converter C2 provoked by the fault on the grid.

To optimize the response of the DC voltage in face of a short-circuit, the minimization of the voltage and current errors in the PI controllers' inputs by the GA procedure is proposed in this article. Each individual (that corresponds to a group of proportional and integral gains) generated by the GA is evaluated by the evaluation function defined as:

$$f_a = \frac{1}{\sqrt{e_{vcc}^2 + e_{id}^2 + e_{iq}^2}} \qquad (16)$$

Where e_{vcc}, e_{id}, and e_{iq} are voltages, current i_d and current i_q errors of the converter C2 control loops, respectively. According to relation (16), the smaller these errors are, the greater will be the evaluation function grade associated with the individual and, then, better will be the gains to be used on the controllers. A schematic representation that describes the problem-formulation procedure is presented in Figure 8.

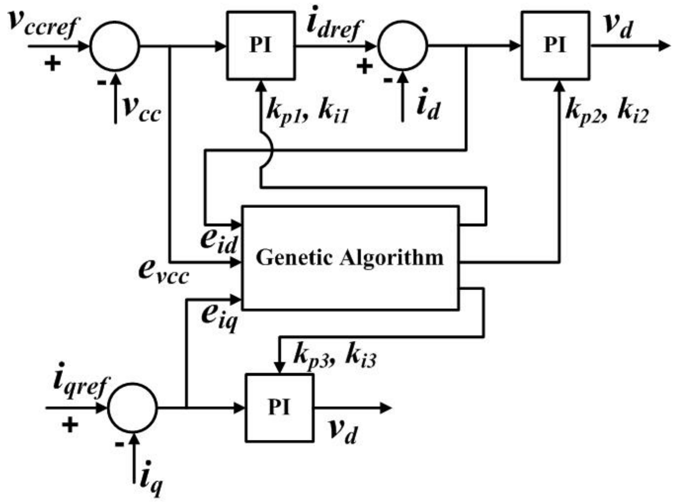

Figure 8. Schematic of the problem formulation

The search space used by the GA to find individuals of greater fitness has been defined based on the gains found by the poles and zeros allocation method described in detail on topics B and C, respectively. Considering the smallest and the largest gain values obtained by the poles and zeros allocation procedure (0.0150 and 32.0588), respectively, the following search space has been used for the GA:

$$\begin{array}{rcccccc} \text{max} & [\,50 & 50 & 50 & 50 & 50 & 50\,] \\ & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \text{individual} & k_{p1} & k_{i1} & k_{p2} & k_{i2} & k_{p3} & k_{i3} \\ & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \text{min} & [0{,}001 & 0{,}001 & 0{,}001 & 0{,}001 & 0{,}001 & 0{,}001] \end{array}$$

The values of the optimum gains found by the GA for a short-circuit situation on the grid are presented in the following section.

VI. RESULTS ANALYSIS

Figure 9 shows the test system implemented on Simulink/Matlab® used to evaluate the control methodologies described on previous sections. The data referred to the grid elements (transformer and lines), as well as the parameters of the wind generator, are presented in detail in the appendix.

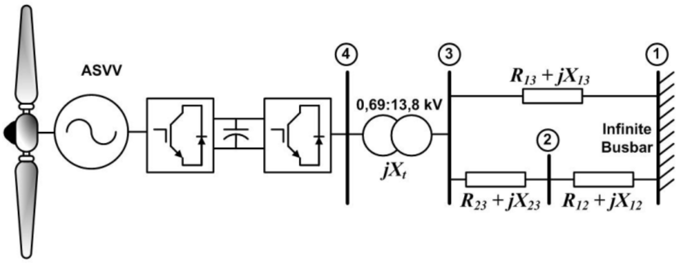

Figure 9. Connection of DDSWG turbine to a double circuit power system model

To calculate the mechanical power of the wind turbine and the input reference speed to the pitch angle control of the turbines (refer to Figure 1), the characteristic curves of $C_p x\lambda$ and maximum power extraction suggested on [12], [13], respectively, were used. The results presented next include the wind generator's operation in two distinct modes:

a) With PI controllers in which proportional and integral gains were projected by the poles and zeros allocation method;

b) With PI controllers in which gains were projected by the GA.

To obtain the gains by the GA, an initial population of 200 individuals to the generation of the descendents was used. From a total of 100 generations, for each one it was simulated on the instant t = 5s, a three-phase short-circuit during 3s on bus 2. The following optimum gains were obtained (refer to Figure 8):

The gains values for the GA adjustment procedures are presented in table 1:

TABLE I. GA GAINS ADJUSTMENTS FOR THE PI CONTROLLERS

	k_p	k_i
PI controller that regulates the current i_{dref}	2,4501	40,4870
PI controller that regulates the voltage v_d	45,2375	39,1848
PI controller that regulates the voltage v_q	49,4688	47,1563

After obtaining the PI controllers' gains by the GA, the test grid was then simulated for each case that was previously specified. In Figure 10, the DC voltage behavior of the wind generator during a short-circuit for the cases (a) and (b), respectively is shown. Expressive damping of the DC voltage during a short-circuit was observed when the gains obtained by PI controllers were used as obtained by the GA project procedure. This is mostly due to the minimization of the voltage and current errors in the input terminals of the controllers, as shown in Figure 11.

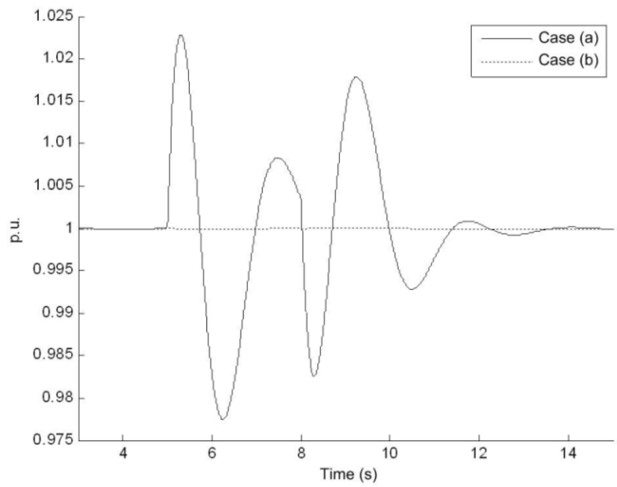

Figure 10. DC-link voltage

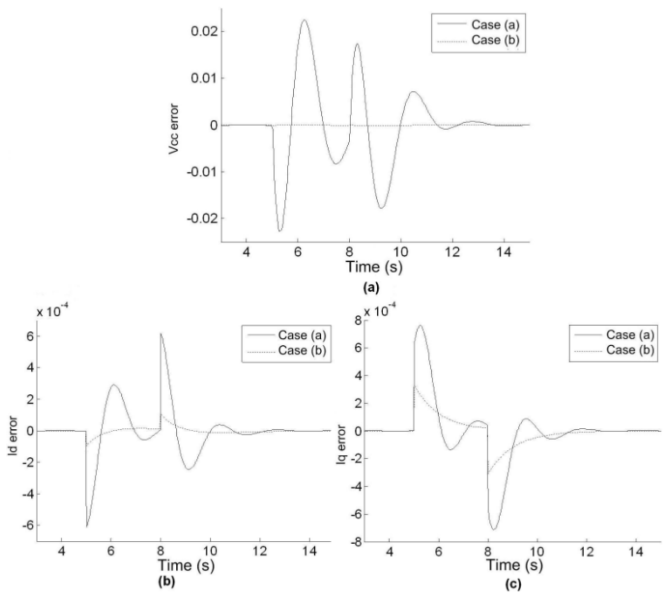

Figure 11. (a) Error between the reference DC-link voltage and the DC-link voltage ; (b) and (c) errors between the reference currents and the currents along the d and q-axis, rescpectively

This performance contributes to maintain the converter in operation during the fault period when the DC link overvoltage and grid-side converter over current may block converter operation, which in this case of the Direct Drive Synchronous Generator implies on the disconnection of the wind system. Through the optimized tuning of the gains, it is also significantly reduced the current peak that the converter C2 injects to the grid during the fault, as shown in Figure 12. This fact is extremely important because it can avoid the wind generator out of service by the action of the over current protection of the wind generator. In other words, this implies that the GA gains adjustment maintains the control loop actions during this critical period what is beneficial to enhance the system transient stability margin.

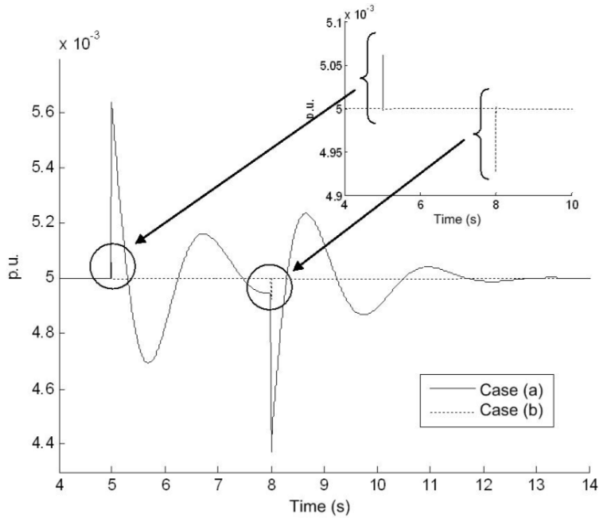

Figure 12. Grid-side converter current

The dynamic behaviors of the terminal voltage and of the active and reactive powers of the wind generator during a short-circuit are presented in Figures 13, 14, and 15, respectively. In particular, it is observed from Figure 15 that at the initial instant of the fault (t = 5s), the converter tends to inject less reactive power to the grid when the PI controllers present optimized gains due to the minimization of the error in the quadrature current i_q, as shown in Figure 16.

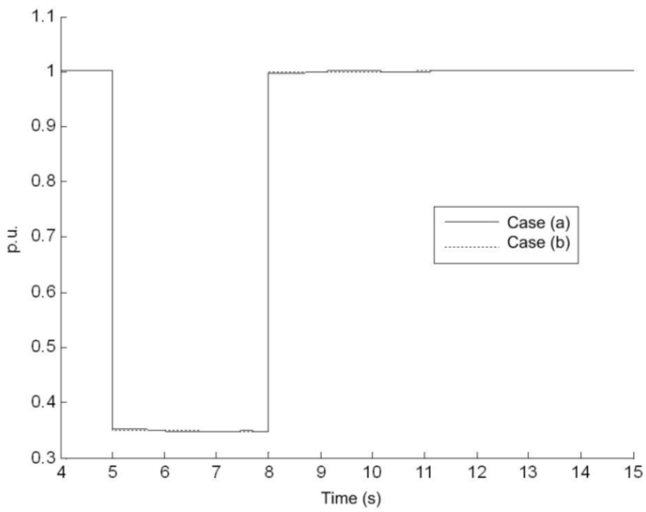

Figure 13. Terminal voltage

However, as mentioned before, a certain control philosophy may be explored in a manner that reaches the requisite level of ride-through-default actually required by the system operator through the injection of a certain amount of this current at the moment of the fault on the grid. The behavior of the current reinforces this conclusion.

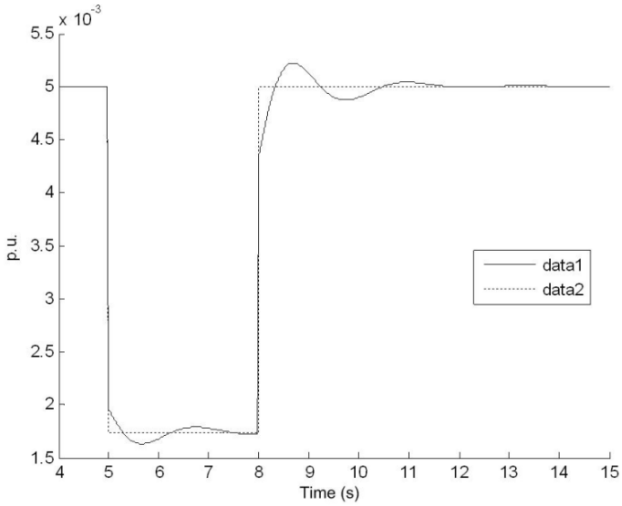

Figure 14. Active power

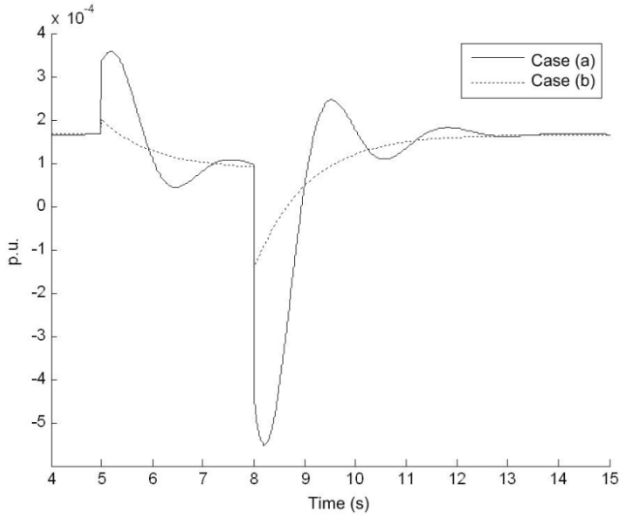

Figure 15. Reactive power

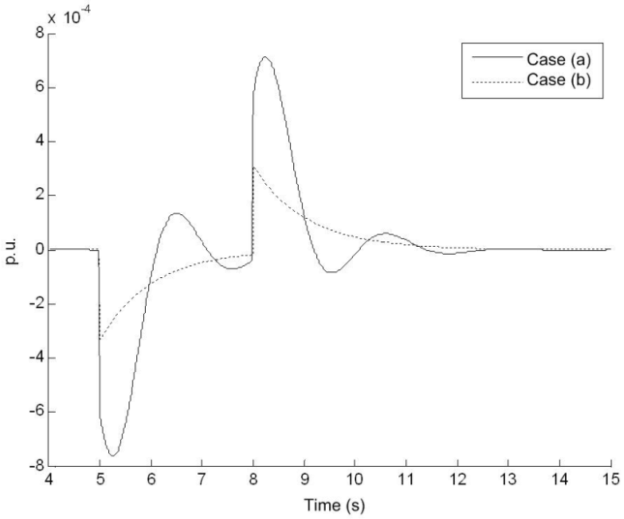

Figure 16. Error between the reference current and the current along the q-axis

VII. CONCLUSIONS

This paper approached the use of the GA on the tuning of PI controllers' gains, in particular, of control loops associated with the converter connected to the grid in a conception of a direct drive wind generator. The results presented have shown that through a fine-tuning of the gains, the peak of the dynamic response of the DC voltage of the wind generator's converters can be significantly reduced in occurrence of a short-circuit on the electrical network, avoiding the use of extra resources like choppers to be necessary. Another important aspect presented in this work is the use of the poles and zeros allocation method instead of the usual trial-and-error method to compare the performance of the proposed GA project procedure. Also, it is extremely important to use the gains obtained by the pole and zero allocation method on the specification of the search interval of the GA. The proposed method in this article may be explored on other control loops of the wind generator in a way to improve ever more the dynamic responses of this kind of technology in face of disturbances on the electrical grids contributing to reduce the problem related with ride through of this system where the grid connection is accomplished through converters.

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