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Evolutionary Algorithm EPSO Helping Doubly-Fed Induction Generators in Ride-Through-Fault

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***Abstract* – A tuning process of the PI (Proportional-Integral) controller gains of a doubly-fed induction generator's (DFIG) rotor side converter is described in this work. The purpose is to tune PI controllers to help the DFIG to survive to network faults, avoiding being tripped-off by under-voltage relays.**

The ride-through-fault capability of DFIGs improves system reliability and allows them to participate in the control and stabilization of a power system following system disturbances. The robust tuning of the DFIG rotor side converter's PI controllers may avoid undesired disconnections from the grid by, for instance, preventing over-currents in its variable frequency AC/DC/AC converter. This work presents an Evolutionary Particle Swarm Optimization-based (EPSO) approach to this tuning, with the aim of helping to limit the line-to-line voltage dip at the DFIG's terminals after a short-circuit, in order to avoid its tripping-off. The EPSO-based algorithm developed is validated at a typical Portuguese 15 kV Distribution Network with the integration of a DFIG, using the transient electromagnetic software package PSCAD/EMTDC™.

***Index Terms* – Doubly-Fed Induction Generator, PI Controller, Evolutionary Algorithms, Particle Swarm Optimization, Ride-Through-Fault Capability**

I. INTRODUCTION

Over the last few years, a majority of wind energy power plants supplying power networks is constituted by variable-speed wind turbines equipped with a doubly-fed induction generator (DFIG). Wind turbines equipped with a DFIG are cost effective and improve the system's efficiency and power quality, comparatively with the conventional ones [1].

In the DFIG concept, the induction generator is grid-connected at the stator terminals and the rotor terminals are connected to the grid via a variable frequency AC/DC/AC converter and a transformer [1-3]. The control of the variable frequency AC/DC/AC converter includes the rotor side and the grid side converter controllers. The objective of the rotor side converter is to manage independently both the stator-side active and reactive powers [4, 5]. The objective of the grid side converter is to keep the DC-link voltage constant regardless of the magnitude and direction of the rotor power [6].

Until recently, wind generators had been designed to be disconnected from the grid if a large voltage dip occurred, to avoid placing the power electronics interconnections in under-voltage conditions that they could not withstand. This could happen as a result of a large network disturbance, such as a short-circuit, and it could trigger a sequence of other events leading to dynamic behaviour problems in the network [7]. This disconnection many times happens precisely when the network needed the support of power injection and, apart from dynamic problems, it did not allow wind generation to give a positive contribution to system reliability. In order to improve the integration conditions of wind energy into power systems, several countries introduced Grid Codes demanding ride-through-fault capability to the manufacturers, who responded positively. For instance, the new Portuguese Grid Code introduced the requirement for DFIG plants to be able to withstand network disturbances that are successfully eliminated according to a predefined profile [8] – defining the threshold for the required ride-through-fault capability (see Fig. 1). In this way, DFIGs will be able to participate in the control and stabilization of the power system following system disturbances [9].

Proportional-Integral (PI) controllers are used in the DFIG variable frequency AC/DC/AC converter control system, due to its simple structure and low cost. PI controllers allow, in general, a quick convergence between the reference and actual values of the active and reactive powers delivered, when a change in the reference values occurs [10]. Especially, the robust tuning of the rotor side converter's PI controllers is of great importance in the dynamic behaviour of the DFIG as, for example, it may prevent over-currents in its variable frequency AC/DC/AC converter [11].

PI controller tuning can be done by several ways, from the classic control theory techniques, such as Ziegler-Nichols method [12, 13], to other methods such as trial-and-error. The classic control techniques offer, in general, solid results but as the controlled system complexity increases, the tuning process also raises its complexity [13]. In the case of the rotor side converter's PI controller tuning, it may be problematical to achieve proper tuning using the classic control techniques. This happens due to the nonlinearity and high complexity of the DFIG control system and, particularly, in the case where the DFIG is in islanding operation, as a result of the stronger coupling between its active and reactive powers delivered. Other PI controller tuning techniques, such as trial-and-error, despite being effective, seem to be "case-dependent" and non-systematic being, therefore, less attractive.

Over the years, meta-heuristic algorithms such as evolutionary algorithms, taboo search and simulated annealing, among others, have been used for nonlinear optimization, due to its high efficiency in searching global optimal solutions on the search space. However, when the

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parameters to be optimized are highly correlated, the performance of these meta-heuristic algorithms seems to degrade [14]. Among these methods, a technique based on swarm intelligence called Particle Swarm Optimization (PSO) has been claimed to be robust in solving continuous nonlinear optimization problems [15]. Related to this as a hybrid or with heritage from both evolutionary and particle swarm optimization algorithms, a new method has recently been proposed: EPSO – Evolutionary Particle Swarm Optimization [16]. It can be viewed either as PSO with evolving weights or as an evolutionary algorithm with a movement rule borrowed from PSO. In comparison with other adaptive evolutionary methods, EPSO is specific in its adaptive recombination operator, while usually the adaptive operator in other evolutionary algorithms is the mutation operator. In terms of particle swarms, EPSO relies on evolving weights in the movement equation, instead of an explicit random factor. Thus, EPSO is less dependent on externally defined parameters by the user, with values that are problem dependent. EPSO has already proven to be efficient, accurate and robust, and with successful applications to power system problems [17 – 20].

This work will detail the tuning of the DFIG rotor side converter's PI controller gains using EPSO, in the case of the occurrence of a short-circuit in the distribution network. The algorithm aims at helping to limit the line-to-line voltage dip at the DFIG's terminals, in order to avoid its tripping-off. The paper presents the model and the specific EPSO-based algorithm applied to a Portuguese Distribution Network case study. The results obtained are also compared and discussed with the results of a trial-and-error PI controller tuning of the same DFIG, under the same conditions. The EPSO-based algorithm solution is validated with the help of the transient electromagnetic software package PSCAD/EMTDC™. In order to evaluate the performance of the proposed algorithm for the tuning of the rotor side converter's PI controllers, operational aspects concerning the grid side converter control will not be detailed, because it is not the main objective of this work.

II. DFIG PI Controller Gain Tuning

A. DFIG Ride-Through-Fault Requirements

The vast majority of wind energy plants integrated into power networks over the last few years is constituted by variable-speed wind turbines equipped with a DFIG. New DFIGs to be integrated must be able to withstand network disturbances that are successfully eliminated. As an example, the Portuguese Grid Code defined a voltage profile which the new DFIGs must be able to survive to in order to avoid tripping-off. This is represented in Fig. 1, where U is the line-to-line root mean square terminal voltage of the DFIG.

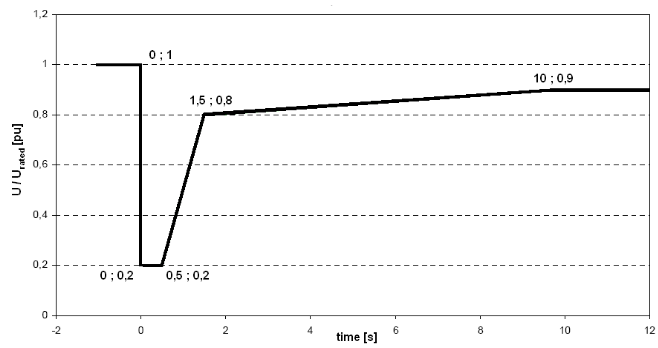

Fig.1. Voltage-time curve required to wind energy plants for surviving voltage dips, according to Portuguese Grid Code [8].

The Portuguese Grid Code requirement for the ride-through-fault capability was defined in order to optimize the integration of wind energy into Portuguese power system, as then DFIGs will be able to participate in the control and stabilization of the power system following system disturbances [8]. Therefore, in order to help DFIGs to withstand network disturbances according to the Portuguese Grid Code requirement for ride-through-fault, this work addresses the tuning of the DFIGs rotor side converter's PI controller gains, using EPSO.

B. Control of the DFIG Rotor Side Converter

In DFIGs, the induction generator is grid-connected at the stator terminals and the rotor terminals are connected to the grid via a variable frequency AC/DC/AC converter and a transformer. The control of the variable frequency AC/DC/AC converter includes the rotor side and the grid side converter controllers. PI controllers are largely used in the variable frequency AC/DC/AC converter control system, due to its simple structure and low cost. Especially, the robust tuning of the rotor side converter's PI controllers is of great importance in the dynamic behaviour of the DFIG as, for example, it may prevent over-currents in its variable frequency AC/DC/AC converter. With this robust tuning, undesired disconnections from the grid can be avoided, increasing, this way, DFIG's reliability and improving power system dynamic behaviour.

Fig. 2 presents a control scheme of the variable frequency AC/DC/AC rotor side converter. This control scheme is based in a stator flux-oriented vector control approach [5]. In this control scheme, there are two independent control loops, being the first related to the active power delivered P_s (by means of the rotor angular speed of the DFIG, ω_r) and the other related to the reactive power delivered, Q_s. The errors between the reference and actual values of ω_r and Qs are processed by PI controllers, which give, respectively, the rotor direct (d) and quadrature (q) reference currents $i_{rd,ref}$ and $i_{rq,ref}$. These d-q rotor reference currents are then transformed into the reference rotor phase currents $i_{ra,ref}$, $i_{rb,ref}$ and $i_{rc,ref}$, via coordinate transformations using the denominated slip angle – φ_{slip}. The obtained reference rotor phase currents are hence compared with the measured ones, by means of a current reference pulse width modulator (CRPWM), generating the gate control signals for the power switches of the converter [21].

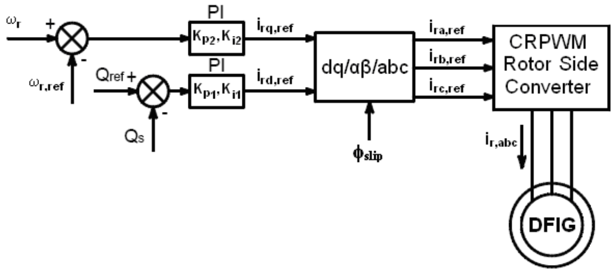

Fig. 2. Control scheme of the variable frequency AC/DC/AC rotor side converter.

In Fig. 2, the PI controller gains K_{p1} and K_{i1} refer to the reactive power control loop, while K_{p2} and K_{i2} refer to the rotor angular speed control loop, which is directly responsible for the active power delivered. The subscript *p* refers to "proportional", while the subscript *i* refers to "integral". The proportional gain changes the PI controller output proportionally to the input's actual error value. The integral gain is proportional to both magnitude and duration of the input's actual error value. By integrating this error value, the integral gain, added to the proportional gain, accelerates the process movement towards the set-point and eliminates the residual steady-state error [12].

The tuning process of the variable frequency AC/DC/AC rotor side converter's PI controllers may be difficult using the classic control techniques, as reported in [11]. This difficulty has to do with the nonlinearity and high complexity of the DFIG control system. Trial-and-error technique seems to be "case-dependent" and, thus, less attractive nevertheless its effectiveness. Moreover, in this work is detailed an EPSO-based algorithm with the purpose of systematizing and simplifying the tuning process of the variable frequency AC/DC/AC rotor side converter's PI controllers, in the case of the occurrence of a short-circuit. The algorithm aims helping to limit the line-to-line voltage dip at the DFIG's terminals in order to avoid DFIG's tripping-off, which by occurring would lead to some network operation issues and losses for DFIG developers. The PI controller gains presented in Fig. 2 (K_{p1}, K_{p2}, K_{i1}, K_{i2}) will be the ones to be tuned using the EPSO-based algorithm, in order to help avoiding undesired tripping-off of the DFIG.

III. EPSO Algorithm: Outline

EPSO (Evolutionary Particle Swarm Optimization) is a population-based meta-heuristic, a variant of the self-adaptive Evolutionary Algorithms (EA) family, where the classical operators for recombination are replaced by a rule similar to the particle movement of Particle Swarm Optimization (PSO) [22]. Therefore, from a conceptual point of view, EPSO allows a double interpretation on how it works, because it may be seen from two perspectives: as a variant of PSO or as a variant of EA. This hybrid conception has the advantage of putting together positive characteristics of both methods.

The variables in an EPSO formulation are divided, according to the vocabulary used in the Evolution Strategies community, in object parameters (the X variables) and strategic parameters (the weights W).

At a given iteration, is considered a set of solutions or alternatives that will be called, as in PSO, *particles*. A particle is a set of object and strategic parameters [X, W]. The particle movement rule for EPSO is illustrated in Fig. 3 and governed by the following rule: at certain iteration k, given a particle $\boldsymbol{X}_i^{(k)}$, a new particle is generated at $\boldsymbol{X}_i^{(k+1)}$ by

$$\boldsymbol{X}_i^{(k+1)} = \boldsymbol{X}_i^{(k)} + \boldsymbol{V}_i^{(k+1)} \quad (1)$$

$$\boldsymbol{V}_i^{(k+1)} = Wi_i^* \boldsymbol{V}_i^{(k)} + Wm_i^* (\boldsymbol{b}_i - \boldsymbol{X}_i^{(k)}) + Wc_i^* \boldsymbol{P}(\boldsymbol{b}_G^* - \boldsymbol{X}_i^{(k)}) \quad (2)$$

$$\boldsymbol{V}_i^{(k)} = \boldsymbol{X}_i^{(k)} - \boldsymbol{X}_i^{(k-1)} \quad (3)$$

where:

- $\boldsymbol{b}_i$ – best point found so far by *i-th* particle;
- $\boldsymbol{b}_G$ – best point found so far by the swarm of particles ;
- $\boldsymbol{X}_i^{(k)}$ – particle *i*, in generation k;
- $\boldsymbol{V}_i^{(k)}$ – velocity of particle *i* in generation k;
- Wi_i – weight conditioning the inertia term (the particle tends to maintain previous movement);
- Wm_i – weight conditioning the memory term (the particle is attracted to its previous best position);
- Wc_i – weight conditioning the cooperation or information exchange term (the particle is attracted to the overall best-so far found by whole swarm);
- $\boldsymbol{P}$ – communication factor – a parameter that induces a stochastic star topology for the communication among particles. It is a diagonal matrix affecting all dimensions of a particle, containing binary variables of value 1 with probability *p* and value 0 with probability (1-*p*); thus, the *p* value controls the passage of information within the swarm.
- * – this symbol denotes that these variables undergo mutations.

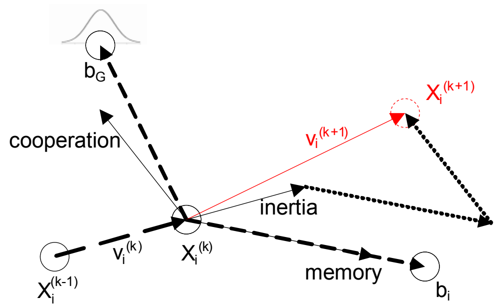

Fig. 3. Movement scheme of a particle (or individual) in EPSO [22].

The mutation schemes for the weights are usually lognormal or multiplicative normal, such as in

$$W^* = W(1 + \sigma N(0,1)) \quad (4)$$

where

- W – any parameter before mutation
- W* – parameter W after mutation
- N(0,1) – Gaussian distribution of 0 mean and standard deviation 1
- σ – mutation or learning rate

The global best b_g is also disturbed as in

$$\boldsymbol{b}_G^* = \boldsymbol{b}_G + Wg^* \boldsymbol{N}(0,1) \quad (5)$$

and the weight Wg is usually mutated according to a Gaussian additive scheme such as in

$$Wg^* = Wg + \sigma_g N(0,1)) \quad (6)$$

where σ_g is a disturbance control parameter or a specific learning rate for this weight.

From an Evolutionary Algorithm point of view, EPSO is a self-adaptive evolutionary algorithm where the operation recombination is self-adaptive and expressed by the *particle movement* rule. This operator *particle movement* seems to be more effective than recombination randomly guided (as it traditionally is) in generating solutions that approach the optimum.

In terms of Particle Swarm Optimization interpretation, EPSO has self-adaptive characteristics, so it does not depend on external definition of weights – these will modify under the influence of selection to improve the search along the iterations. Because it is self-adaptive, EPSO seems to become more robust than PSO and more insensitive to parameter initialization [16]. In addition, EPSO modifies slightly the PSO concept, by defining a blurred target − Eq. (5) − for the global best instead of a single point, has also been demonstrated to improve the quality of the results.

In every algorithm step, each particle is replicated a certain number of times (usually once is enough). Afterwards, each replica of the particle has its strategic parameters (weights) mutated. All replicas and an original particle generate descendent particles through recombination, according to the particle movement rule described. The evaluation (calculation of fitness) of each descendant is followed by a selection procedure which ensures that the best offspring from each particle form a new generation.

By mutation and selection, the particles *learn* the values of their strategic parameters. Because the recombination operator is not neutral (the movement rule in PSO is enough to push particles to the zone of the optimum), this combined effect has a beneficial consequence in the discovery of the optimum.

IV. DFIG PI Controller Gain Tuning Using EPSO Algorithm

A. The test case

In order to optimize the integration of wind energy in the Portuguese power system, DFIGs must be able to participate in the control and stabilization of the power system following system disturbances [8]. This is mostly achieved by DFIG's capability to ride through network disturbances, according to a defined voltage profile by the Portuguese Grid Code (Fig. 1).

This work presents the tuning of the variable frequency AC/DC/AC rotor side converter's PI controllers, in the case of the occurrence of a short-circuit at the distribution network, by means of the application of EPSO. The EPSO-based algorithm is operated once and offline, before the first-run of the DFIG to be tuned. The algorithm, which aims to be generic for any DFIG control design, aims at helping in limiting the line-to-line voltage dip at the DFIG's terminals by tuning the rotor side converter's PI controllers, in order to avoid DFIG's tripping-off after a short-circuit at the distribution network. Thus, DFIG's reliability can be enhanced, by avoiding undesired tripping-off and, thus, the whole power system dynamic behaviour can be improved. In the following sections, operational aspects concerning the grid side converter control will not be detailed as the main objective of this work is to evaluate the performance of the proposed EPSO-based algorithm.

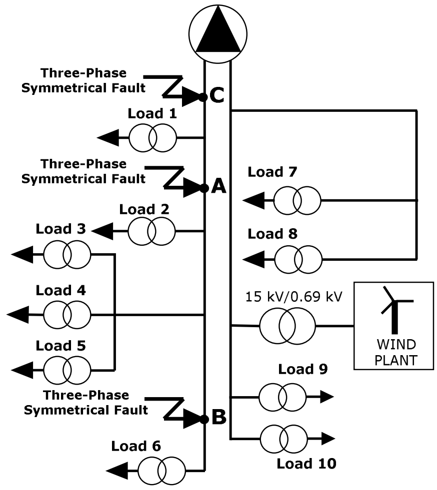

Fig. 4. Distribution network scheme used in simulation tests.

In order to validate the EPSO-based algorithm, the power system of Fig. 4 was modelled in the PSCAD/EMTDC^{TM} environment.

The power system represented in Fig. 4 is a typical sub-set of a 15 kV distribution network in Portugal with the inclusion of a single variable speed wind turbine equipped with a DFIG (Wind Plant). At this voltage level disturbances that may lead to the DFIG's tripping-off are frequent. Two distribution lines are connected to the primary 60/15 kV distribution substation, and supply ten LV distribution substations modelled as load impedances. The high-voltage distribution network above the 60/15 kV Substation is represented by an equivalent, with a short-circuit power equal to 250 MVA, being the reactance to resistance ratio equal to 1.5. The example is based on real data, modified to publication purposes.

B. The EPSO model

The variable frequency AC/DC/AC rotor side converter controller of the DFIG is the one described in Fig. 2. Therefore, there are two proportional gains (K_{p1}, K_{p2}) and two integral gains (K_{i1}, K_{i2}) to tune. The pre-fault operating point of the machine corresponds to a rotor angular speed, ω_{pre}, equal to 1.01 p.u. on the machine rating, at a constant wind speed of 15 m/s. The pre-fault direct rotor current, i_{rd_pre}, is equal to 0.34 kA and the pre-fault quadrature rotor current, i_{rq_pre}, is equal to 0.32 kA. The parameters of the simulated power system shown in Fig. 4 are given in the Appendix.

Each set (a 4-tuple) of possible tunings for the PI controller gains (K_{p1}, K_{p2}, K_{i1}, K_{i2}) will be from now on called *particle*. So, each particle *i* position in the search space will refer to a set of possible PI controller gain tunings, that is, X_i= [K_{p1}, K_{p2}, K_{i1}, K_{i2}].

The fitness of each particle will rely on the response of the DFIG control system to a three-phase symmetrical fault of 500 ms duration at the middle of one of the distribution lines shown in Fig. 4 (as point *A*), in terms of the line-to-line voltage dip at the DFIG's terminals.

The EPSO-based algorithm for the tuning of the PI controller gains shown in Fig. 2 is operated once and offline, before the first-run of the DFIG shown in Fig. 4. The algorithm is described as follows, from **Step 1)** to **Step 12)**.

Step 1) Specification of EPSO parameters:

- Maximum number of iterations: *itmax* = 100
- Number of particles: $N = 15$
- Noise rate to disturb the global best ($\boldsymbol{b}_G$): $\sigma_G = 0.001$
- Strategic parameters mutation ratio: $\sigma = 0.1$
- Communication factor conditioning matrix $\boldsymbol{P}$: $p = 0.2$
- Upper bound position of the particles: $\boldsymbol{X}_{max}$ = [25; 25; 25; 25]
- Lower bound position of the particles: $\boldsymbol{X}_{min}$ = [0.01; 0.01; 0.01; 0.01]
- Upper bound velocity of the particles: $V_{max} = X_{max} \times 0.2$
- Lower bound velocity of the particles: $V_{min} = -X_{max} \times 0.2$

Step 2) Random initialization of the particle positions ($\boldsymbol{X}_i$) and their velocities ($\boldsymbol{V}_i$), setting of the initial personal ($\boldsymbol{b}_{,i}$) and global best positions ($\boldsymbol{b}_G$), initialization of the strategic parameters for each particle *i* [inertia (Wi_i), cooperation (Wc_i), memory (Wm_i) and noise *(Wg)*];

Step 3) Replication of each particle *i*, creating $\boldsymbol{X}\_m_i$, the velocity V_m_i and the initial positions $\boldsymbol{b}_{,i}\_m$ and $\boldsymbol{b}_G\_m$, where the letter *m* refers to mutated;

Step 4) The strategic parameters for each particle *i* (inertia, cooperation and memory) are mutated to give Wi_m_i, Wc_m_i and Wm_m_i, respectively.

Step 5) At this moment, a new velocity for each particle *i*, V_i^{new}, is updated by the Equation (1). The same process is done to obtain $V\_m_i^{new}$, with the mutated values of the strategic and object parameters. The velocity parameter of each particle V_i (and V_m_i) is then evaluated for limits violation [V_{min}, V_{max}]. If this happens, it is set to the relevant upper or lower bound value (V_{min} or V_{max}).

Step 6) Based on the updated velocity, each particle *i* then changes its position, $\boldsymbol{X}_i$, according to the Equation (2), to $\boldsymbol{X}_i^{new}$. The same process is done to obtain $\boldsymbol{X}\_m_i^{\text{new}}$. The position of each particle $\boldsymbol{X}_i$ (and $\boldsymbol{X}\_m_i$) is then evaluated for limits violation [$\boldsymbol{X}_{min}$, $\boldsymbol{X}_{max}$]. If this happens, it is set to the relevant upper or lower bound value ($\boldsymbol{X}_{min}$ or $\boldsymbol{X}_{max}$).

Step 7) For each particle *i*, run a power system dynamic simulation. At instant t_0, application of a three-phase symmetrical fault at point *A*, with 500ms duration. Measurement, for each particle *i*, of the minimum post-fault line-to-line terminal voltage of DFIG, U_{t_min} (in per unit values).

Step 8) Calculation of the evaluation value of each particle *i* (normal and mutated) in the population, using the fitness function *F* whose objective is to be minimized – Equation (3).

$$F_i = \frac{1}{U_{t\_\min}} \tag{7}$$

The evaluation value of each particle *i*, given by fitness function *F*, is as "fit" as it is lower. In other words, the purpose of each particle *i* is to decrease its evaluation value *F*.

Step 9) Comparison of each particle *i* present position, $\boldsymbol{X}_i$, with its personal best ($\boldsymbol{b}_i$) based on the fitness evaluation (see Equation (3)). If the current position $\boldsymbol{X}_i$ is better than $\boldsymbol{b}_i$, then $\boldsymbol{b}_i = \boldsymbol{X}_i$. If $\boldsymbol{b}_i$ is updated, then compare each particle's $\boldsymbol{b}_i$ with the population global best position $\boldsymbol{b}_G$ based on the fitness evaluation. If $\boldsymbol{b}_i$ is better than $\boldsymbol{b}_G$ then $\boldsymbol{b}_G = \boldsymbol{b}_i$. The same process is done to the mutated particles.

Step 10) Comparison if $\boldsymbol{b}_G$ is better than $\boldsymbol{b}_G\_m$, based on the fitness evaluation (Fi versus F_m_i). If $\boldsymbol{b}_G\_m$ is better than $\boldsymbol{b}_G$, $\boldsymbol{b}_G = \boldsymbol{b}_G\_m$. If g_{best} is updated, the mutated strategic parameters substitute the normal ones, i.e., $Wi_i = Wi\_m_i$, $Wc_i = Wc\_m_i$ and $Wm_i = Wm\_m_i$.

Step 11) If the number of iterations reaches the maximum (*itmax*), then continuous onto Step 12). Otherwise, go back to Step 4).

Step 12) The particle that generates the latest global best (g_{best}) is the optimal solution of the problem, in this case, the optimal set of PI controller gains (K_{p1}, K_{p2}, K_{i1}, K_{i2}).

C. Performance of the EPSO-based Algorithm

The results of the application of the EPSO-based algorithm at the power system shown in Fig. 4 are shown as follows. A three-phase symmetrical fault of 500ms duration is simulated at the middle of one of the distribution lines shown in Fig. 4 (point *A*), at t_0= 5 s. This simulated fault intends to represent a severe disturbance at the distribution network, with the aim of evaluating the performance of the developed EPSO-based algorithm.

For evaluating the EPSO-based algorithm, a trial-and-error design of the PI controllers is provided. In this process, classical techniques were used to obtain initial values for the PI gains of the controllers. Then, the gains were carefully adjusted by trial-and-error through several simulations, in order to obtain minimum variations in the DFIG's terminal voltage U_t when faults occur. After this long process of tuning, the values obtained for the PI gains are presented in Table I.

TABLE I – PI CONTROLLER GAIN VALUES OBTAINED USING TRIAL-AND-ERROR

PI CONTROLLER GAIN VALUES			
K_{p1}	K_{i1}	K_{p2}	K_{i2}
3.60	3.90	4.30	4.30

Fig. 5 presents the DFIG's terminal voltage U_t from a simulation with PSCAD/EMTDC™, being the PI controller gains the ones given in Table I. U_{t_RTF} is the voltage profile required by the Portuguese Grid Code, which is parameterized at the DFIG's protection relay. With the values in Table I, in the event of a short circuit in the location defined, the terminal voltage at the DFIG will change in such a way that the voltage profile demanded by the Grid Code is not met and protections will trip, disconnecting the generator, which is undesirable.

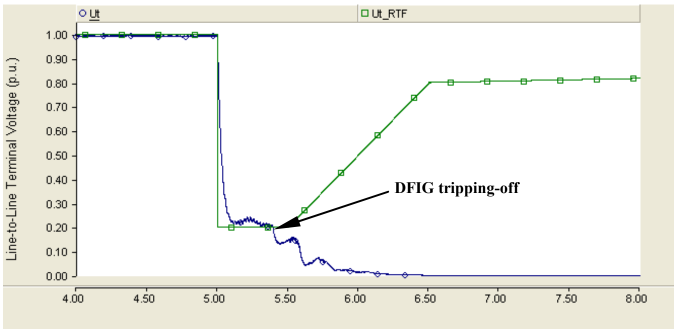

Fig. 5. Simulation if the evolution of the terminal Voltage U_t of the DFIG when controller parameters are defined by trial-and-error, and comparison with the RTF demand from the Portuguese Grid Code, having the fault occurred at point A.

After launching the EPSO algorithm, one could improve the controller tuning. Table II shows the PI controller gain values obtained from the EPSO best solution and the associated minimum line-to-line post fault terminal voltage of the DFIG, U_t, calculated from simulation with PSCAD/EMTDC^{TM}. Fig. 6 presents DFIG's terminal voltage U_t being the PI controller gains obtained from EPSO, given in Table II.

TABLE II – OPTIMAL PI CONTROLLER GAIN VALUES AND MINIMUM LINE-TO-LINE POST-FAULT TERMINAL VOLTAGE OF THE DFIG USING EPSO

PI CONTROLLER GAIN VALUES			
K_{p1}	K_{i1}	K_{p2}	K_{i2}
0.40	12.48	1.1	7.69
MINIMUM LINE-TO-LINE POST-FAULT TERMINAL VOLTAGE OF THE DFIG			
$U_{t\ min}$ (p.u.)			
0.2148			

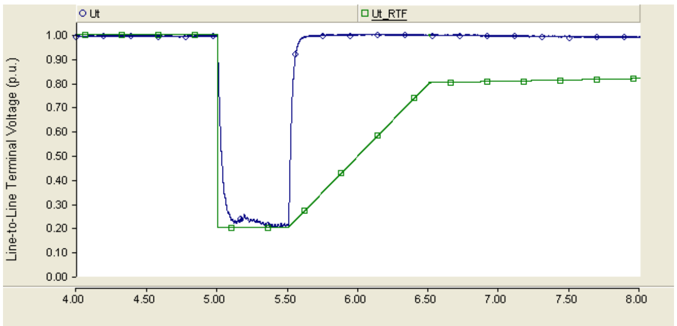

Fig. 6 – Terminal Voltage U_t of the DFIG using EPSO, having the fault occurred at point *A*.

Fig. 7 shows the evolution of the fitness function *F* during the iterative process of EPSO (maximum number of iterations equal to 100), illustrating the progress of the optimization procedure.

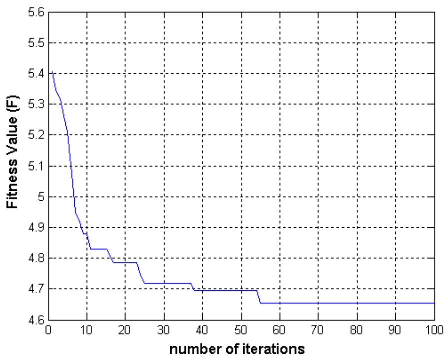

Fig. 7 – Performance of the fitness function *F*.

For assessing the enhancement of the DFIG's performance due to the EPSO-based algorithm, the same fault is tested in two other locations: *B* and *C* (see Fig. 4). PI controller gains remain the same as shown in Table I and Table II for trial-and-error and EPSO, respectively.

In Fig. 8, one can see DFIG's terminal voltage U_t being the PI controller gains obtained from trial-and-error as given in Table I. The fault occurring at t_0= 5 s is at point *B*.

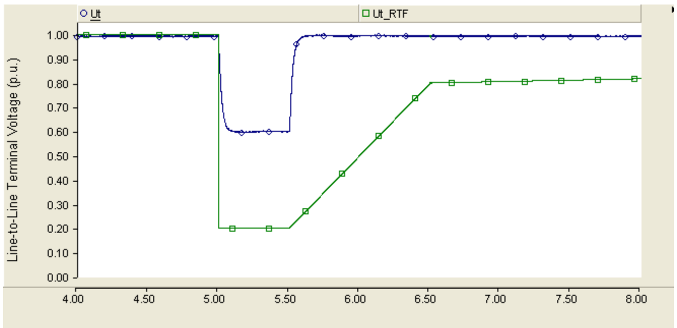

Fig. 8 – Terminal Voltage U_t of the DFIG using trial-and-error, having the fault occurred at point *B*.

Fig. 9 shows DFIG's terminal voltage U_t being the PI controller gains obtained from EPSO, given in Table II. The fault occurring at t_0= 5 s is still at point *B*.

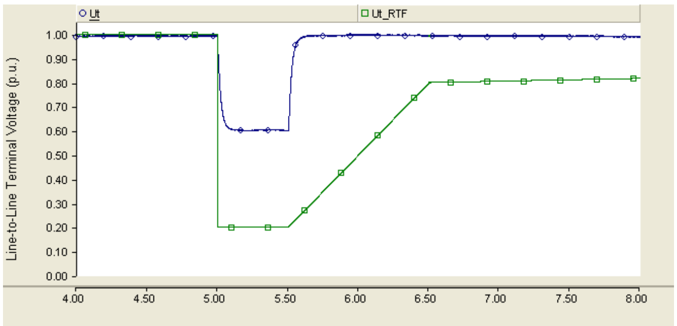

Fig. 9 – Terminal Voltage U_t of the DFIG using EPSO, having the fault occurred at point *B*.

In Fig. 10, one can see DFIG's terminal voltage U_t being the PI controller gains obtained from trial-and-error as given in Table I. The fault occurring at t_0= 5 s is now at point *C*.

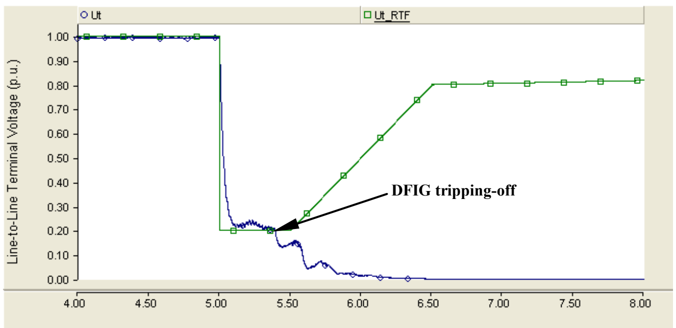

Fig. 10 – Terminal Voltage U_t of the DFIG using trial-and-error, having the fault occurred at point *C*.

Fig. 11 shows DFIG's terminal voltage U_t being the PI controller gains obtained from EPSO, given in Table II. The fault occurring at t_0= 5 s is at point *C*.

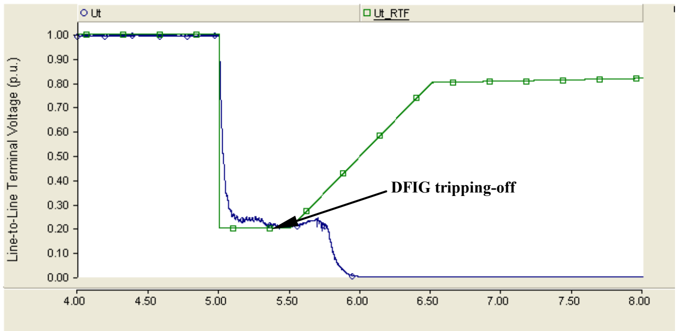

Fig. 11 – Terminal Voltage U_t of the DFIG using EPSO, having the fault occurred at point C.

V. DFIG PI Controller Gain Tuning Using EPSO Algorithm: Discussion

A robust tuning of the DFIG rotor side converter's PI controllers may avoid undesired disconnections from the grid, as it may limit the terminal voltage dip at DFIG's terminals. Thus, DFIG's reliability can be enhanced and the whole power system dynamic behaviour can be improved. As PI controller gain tuning process using the classic control theory techniques may be complex and the trial-and-error technique is non-systematic, an EPSO-based approach was developed in this work for the PI controller tuning process.

The correct tuning of generator controllers must result from a system analysis and cannot be done at the factory. Complying with regulations on Ride-Through-Fault-Capability is therefore a process that not only depends on manufacturers but also on cooperation between wind farm owners and distribution system operators (or transmission system operators). This cooperation is mandatory in order to be able to adequately tune the parameters or gains of DFIG controllers in order to have the generators comply with system requirements.

The results obtained by the application of the EPSO-based algorithm have demonstrated that one is able to reach an efficient tuning of the PI controller gains. The EPSO-based algorithm, with its strategic parameter self-adaptive capability conducted to superior results compared a trial-and-error approach. In the example shown in the paper, the tuning of the rotor side converter's PI controllers using EPSO allowed the DFIG to remain connected to the network on the fault occurred in point *A*, in opposition to the case where the PI controller gains were obtained from trial-and-error. Indeed, the EPSO-based algorithm allowed a larger range in the distribution network sub-set considered where the Portuguese Grid Code's Ride-Through-Fault requirements can be accomplished, in comparison with the trial-and-error design. It is considered that both protections at the secondary side of the wind power plant and at the primary substation allow the Ride-Through-Fault requirements (see Fig. 1).

This paper presents therefore a systematic approach to an optimal design of rotor side converter PI controllers for DFIG applied in wind generation, allowing the machines to respect the requirements for Ride-Through-Fault capability imposed by several system operators. This is seen as an important contribution to increase the reliability and security of the operation of distribution networks with large penetration of wind power generation.

Appendix

Wind Turbine

	value	unit
Rotor Radius	22	m
Blade Angular Speed	1.904	rad/s
Air Density	1.225	kg/m^3
Number of Blades	3	
Gearbox Ratio	55	

Doubly-Fed Induction Generator (p.u. values on base of the machine rating)

Rated Power	660	kW
Nominal Voltage	0.69	kV
Stator Resistance	0.0067	p.u.
Stator Leakage Reactance	0.03	p.u.
Rotor Resistance	0.0058	p.u.
Rotor Leakage Reactance	0.0506	p.u.
Magnetizing Reactance	2.3161	p.u.
Angular Moment of Inertia	3.5	s
Rated Slip	2	%
Poles	4	

Step-up Transformer

Rated Apparent Power	1	MVA
Nominal Voltage	0.69/15	kV
Leakage Reactance	6	(%)

Wind Energy Plant's Power Converters

Power Converter Coupling Transformer

Rated Apparent Power	100	kVA
Nominal Voltage	0.69/0.3	kV
Leakage Reactance	9.5	(%)

DC-link

Capacitor Value	13.62	μF
DC-link Voltage	0.36	kV

Three-Phase Symmetrical Fault Parameters

Symmetrical Fault Impedance	1.25	Ω

High-Voltage Distribution Network Parameters

Short-Circuit Ratio	250	MVA
Reactance to Resistance Ratio	1.5	
Nominal Voltage	60	kV

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