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Research Article

Performance Enhancement of a Wind Power System Based on Bee Colony Optimization Approach

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Abstract

This paper presents suitable designs of Proportional-Integral (PI) controllers for Rotor Side Converter (RSC) and Grid Side Converter (GSC) of wind turbine generator type Doubly Fed Induction Generator (DFIG) in order to control the current, voltage, and the power in RSC side and the power in GSC side of Wind Energy Conversion System (WECS). Besides, the proposed controllers have been designed to reduce the overshoot fault current when different types of disturbances occurred. The optimal parameters design of the proposed PI controllers is presented too by using intelligent technique namely; Bee Colony Optimization (BCO). The first stage of this paper includes the constriction of PI controller based on trial and error method in order to study the full performance of the WECS system. The second stage contains the construction of an intelligent controller; PI based BCO in order to get the optimal parameter design that meets all the requirements. In each stage, the wind speed has taken to be fixed and variable. Three types of faults have been implemented at the terminal of wind generator namely; Single Line to Ground fault (SLG), Double Line to Ground fault (DLG), and Three Line to Ground fault (TLG). The proposed approach has been implemented on a wind energy system connected to a network similar to Iraqi national network in voltage magnitude and frequency. Finally, the study shows that the use of PI controller based BCO is a suitable choice for reducing the overshoot fault current and in enhancing the full performance of WECS.

Keywords: *Proportional-Integral, Rotor Side Converter etc.*

Introduction

The energy demands are vast, and the world needs to generate large quantities of electric power. This demand has typically been met with use of fossil fuels energy, but the world has set aspirations and target to minimize emission from generation power by fossil fuels role and increase the renewable energy technologies. The renewable energy does not produce harmful emission during its operation (C. Donald Nicolson, 2004). Energy of wind is one of the most important sources of renewable energy that is growing up very fast day after day, which the wind turbines convert the kinetic energy of winds into a mechanical energy and the last is converted to electrical energy throughout the generators. The wind turbine may be connected directly to the grid or operates as stand-alone units at the farms, villages and islands for small power capacity where the access to the network is costly or remote. The main parts of wind turbine system are shown in Fig. 1. Aerodynamic, mechanical and electrical aspects are the three basic aspects of the Wind Turbine Generator System (WTGS) (M. Altimania, 2014).

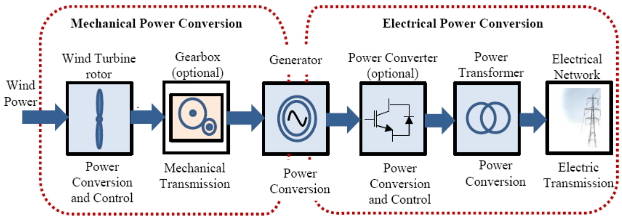

Fig. 1 Block diagram of WTGS components (M. Altimania, 2014)

Generally, wind turbines are situated at an inaccessible place (mountainous, green lands and off-shore) which be very severe as a working environment. Each component of the wind turbine generator systems is subjected to be failed due to temperature variation, material corrosion, mechanical stress, voltage stress and electrical line faults.

Line faults are a main problem in a power system. The short circuit current has an effect on the wind turbine behavior. Fault current in the line can be more than the normal current flowing in the line before the fault in several times. Therefore, a fast procedure should be taken to reduce the overshoot fault current in order to keep the system in a stable state.

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The fault can be Double Line to Ground or Single Line to Ground where a single line or double line faults are shorted to ground or connected together, while the three lines faults are much dangerous and for which they are used at analysis for determining the maximum current which should be interrupted. Fig. 2 shows the failure number distribution in the percentage of wind power plants where the failure of electrical is system equal to (17.5%) and generator failure is equal to (5.5%) (Y.Amirat and *et al*, 2007), (Qian Lu, 2011).

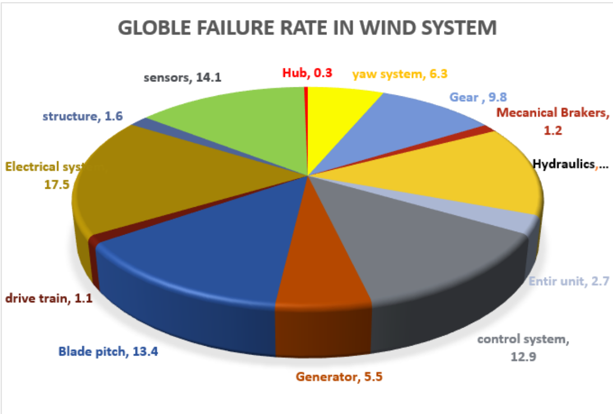

Fig. 2 Failure number distributions percentage for wind power plants (Y.Amirat and *et al*, 2007).

Several papers have covered different controlling methods of WECS to reduce the overshoot fault current when different types of faults occur in the system. An optimal parameters design of PI controller equipped with Particle Swarm Optimization (PSO) techniques is used in (D. Nagaria, G.Pillai and H.Gupta, 2010) to show a better transient behavior of WECS. In (P. Chakravarty and G. Kumar Venayagamoorthy, 2011) The nonlinearity in DFIG and the complexity of the grid leads to fail the traditional method to find the PI parameters. A new heuristic approach, the Mean Variance Optimization (MVO) method is used for online tuning of PI controller on RSC of DFIG. A new technique in (A. El-Naggar and I. Erlich, 2017) to reduce the short-circuit current of Doubly-Fed Induction Generator (DFIG) of Wind Turbines (WT) without adding extra components is used based on the open-loop and the close-loop dynamic response of the DFIG.

The main topic of this paper is to perform the action of (DFIG) and reduce the overshoot fault current of Doubly Fed Induction Generator (DFIG) system under different types of faults by using conventional PI controller or PI controller combined with one of the intelligent techniques namely; Bee Colony Optimization (BCO) technique in order to find the optimum parameters design of PI controller that give minimum overshoot fault current.

Doubly Fed Induction Generator (DFIG)

Basically, the DFIG is a Wound Rotor Induction Generator (WRIG). In order to achieve a variable speed operation, the rotor circuit of this type can be controlled by external devices. Fig. 3 shows the DFIG typical block diagram system. The generator's stator is connected by a transformer to the grid, while the generator's rotor is connected by power converters, transformer and harmonic filters to the grid. The range of power for DFIG is normally between hundred kilowatts to several megawatts. The generator's stator is responsible for delivering the power to the grid from wind turbine, therefore, the power in this part is unidirectional, while in the rotor circuit the power flow is bidirectional depending on the operating conditions. Through the Grid Side Converters (GSCs) and Rotor Side Converter (RSCs) the power can be delivered from the grid to the rotor and vice versa. When the maximum power of rotor is approximately 30% of the stator rated power, the power rating of the converters is substantially reduced in comparison to the WECS with full-capacity converters (B. Wu and *et al*, 2011).

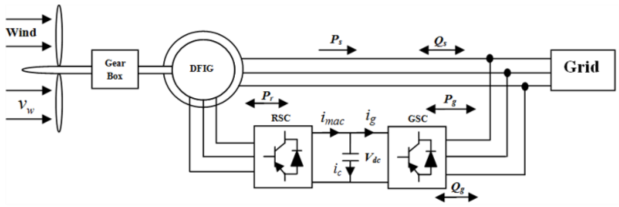

Fig. 3 Block diagram for DFIG variable speed wind energy conversion system (B. Wu and *et al*, 2011)

The DFIG can therefore operate at sub-synchronous speeds, synchronous speed and super-synchronous speeds. With the assumption that the system is lossless, for sub-synchronous speed generation, power is delivered from the stator but the rotor consumes power. For synchronous speed generation, the rotor frequency is zero; therefore, rotor currents are dc and the total rotor power is zero. The DFIG delivers power only from stator. For super-synchronous speed generation, both stator and rotor deliver power to the grid. A wind turbine with a DFIG can use this benefit during high wind speed operation. This is one of the advantages of the DFIG over other variable speed generators (Warachart Sae-Kok, 2011).

Proportional Integral (PI) Control

It is one of the main components that have been used during this work. Fig. 4 shows the typical structure of PI control. In PI controller, it can be seen that the error signal e(t) is used to generate the integral actions and proportional, with the resulting signals summed and weighted in order to form the control signal u(t), the last signal is applied to the planet model. Equation (1) shows the mathematical representation of PI Controller (T. Unchim and *et al*, 2011).

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)\,d\tau\right) = u_p(t) + u_i(t) \qquad (1)$$

Where:

- K_p represents proportion gain.
- T_i represents integral time constant of PI controller.
- u(t) represents the input signal to the plant model.
- *e(t)* represents the error signal is defined as $e(t) = r(t) - y(t)$.
- *r(t)* represents the reference input signal.

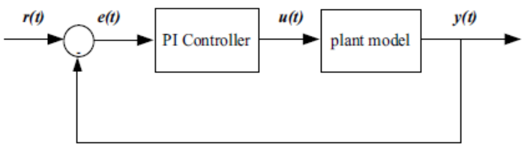

Fig. 4 A typical PI controls structure (T. Unchim and *et al*, 2011).

The controller and feedback transfer functions can be equivalently written as Equation (2) (T. Unchim and *et al*, 2011).

$$G(s) = K_p\left(1 + \frac{1}{T_i s}\right) \quad (2)$$

System Modelling

A. Simulation of DFIG connected to Iraqi national network

In this simulation, a 9 MW wind farm system including six generators each 1.5 MW is simulated. This wind farm is connected to system has voltages and frequency similar to the Iraqi National Network as shown in Fig. 5. A Doubly-Fed Induction Generator (DFIG) is the type of generator that used in this wind farm and an AC/DC/AC IGBT based PWM converter. The stator of DFIG is linked directly to the 50 Hz grid and the rotor is connected through AC/DC/AC convertor at variable frequency.

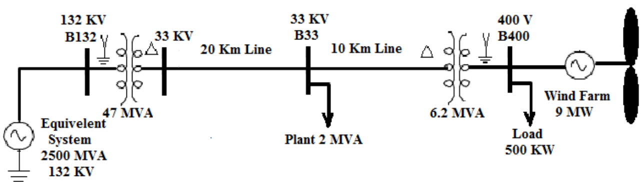

Fig. 5 Single line diagram of the wind farm connected to Iraqi national network

For DFIG simulation, the basic equations of the induction generator are used to develop the proposed model by using phase variables and (abc) to (dq) transformation (Park transformation). The simulation of overall system that used in this work is shown in Fig. 6 which consists of wind farm connected with grid. The symmetrical and unsymmetrical faults have been applied at terminals of generators to study the performance of DFIG, then a proper software used to minimize the overshoot fault current and to performance the wind turbine action using intelligent controller.

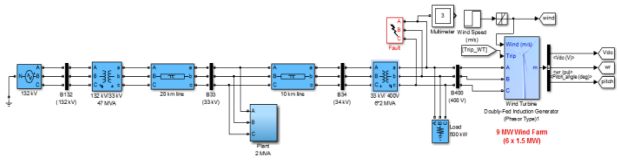

Fig. 6 Simulation of DFIG connected to Iraqi National Network

B. Control strategy of the proposed system

The PI controller is normally used due to its simple structure and ability to apply to a wide range of dynamic control system. Many traditional tuning methods were used for tuning the gain of PI controller such as trial and error tuning method. In some cases, this method doesn't assure good tuning results and tend to produce a steady state error and higher overshoot current. In order to improve the capabilities of the traditional PI parameters tuning techniques, several intelligent techniques have been suggested to improve the PI tuning such as BCO and ANN techniques that can find the optimum parameters of PI controller. There are four PI controllers used in this work for voltage, current, and power control in rotor side and grid side converter of DFIG system due its structure simplicity and its ability for applying a wide range of situations.

1. Simulation of Rotor-Side Converter (RSC) with intelligent techniques

The main aim of this controller is to control the rotor current of DFIG for reactive and active power flow control, voltage and the power in rotor side.

In order to improve the traditional PI tuning method and to find optimum gains of PI controller, the intelligent tuning method is used in this work which depends on Integral Time Square Error (ITSE) for providing better PI tuning of the controller. The (ITSE) is done by using integrator, math function, to work space, clock and product blocks. These blocks connected to the error signal to the rotor side convertor and grid side convertor. PI controller based on intelligent technique with three controllers are shown in Figures (7 to 9).

2. Simulation of Grid Side Converter (GSC) with intelligent techniques (RSC)

Grid side convertor can be used for DC bus regulation between two converters. Commonly it is set to a unity power factor or in such a way to achieve the required strategy. Therefore, Different strategies of control can be used. The most common strategy is Park-Clark (abc to dq transformation). Reference current obtained from DC bus voltage also voltage reference is achieved by using (PI) controller to absorb or supply active power. Furthermore, the control strategy of (GSC) is much complex where the control of the machine must be in sub synchronous and super synchronous modes and gets maximum output power of the wind turbine (E. Tremblay and A. Chandra, 2006). PI controller based on intelligent technique of GSC for power grid control is simulated in Fig. 10.

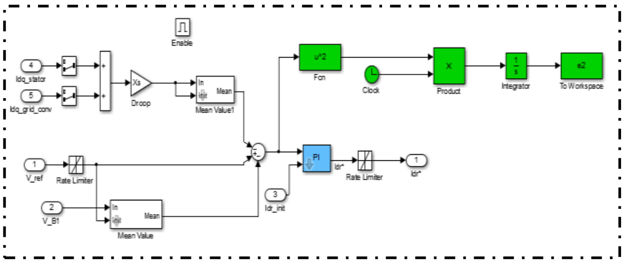

Fig. 7 Rotor side convertor - voltage control system in DFIG

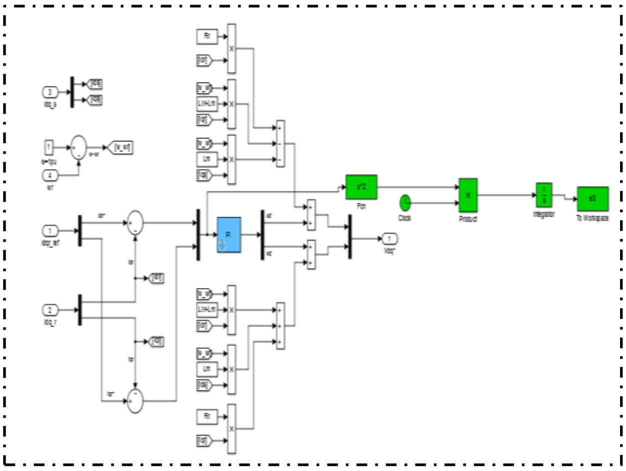

Fig.8 Rotor side convertor - current control system in DFIG

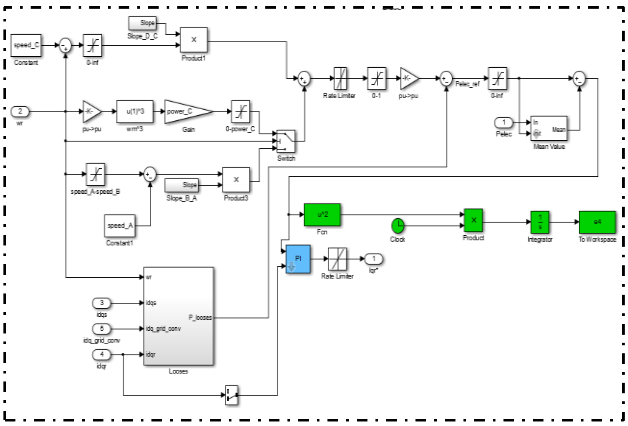

Fig. 9 Rotor side convertor - power control system in DFIG

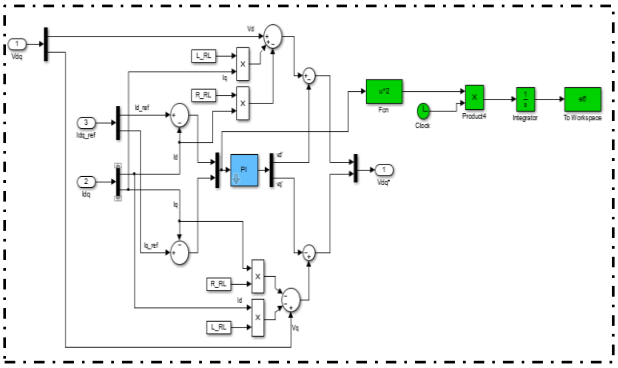

Fig. 10 Grid side convertor - current control system in DFIG

Bee Colony Optimization (BCO) Optimization Technique

Karaboga in 2005 (M. Khalaf Kadhim, 2014) presented the BCO swarm algorithm to optimize numerical problems. The BCO algorithm was inspired by the intelligent invasion behavior of honey bees.

The model contains three important elements: unemployed foraging bees, employed foraging bees and food sources. The rich food sources close to the hive which is the third component is searched by the employed and unemployed foraging bees. Two major techniques of behavior are important for additive intelligence and self-arrangement are defined by the model (Dervis Karaboga, 2005):

1- Positive feedback is giving to rich food sources to recruit by foragers.
2- Negative feedback is giving to poor food sources abandoned by foragers.

In BCO algorithm, agents (artificial forager bee's colony) look for profit food sources). To apply BCO algorithm first of all, the optimization problem tries to find the best parameter vector that minimizes an objective function. By applying the actions, movement to the best results, the artificial bees detect the population of primary solutions and then repetitively improve them.

Proposed BCO based PI parameters

Detailed of the BCO Algorithm used in this work are as follows:

1: Initiate the population solutions xi, j.
2: Compute the population.
3: Cycle=1.
4: Generate new food source location (solutions) $V_{i,j}$ next to $X_{i,j}$ for the employed bees using the equation (3):

$$V_{i,j} = X_{i,j} + \Phi_{i,j} (X_{i,j} - X_{k,j}) \quad (3)$$

(Φ is a random value in the range of [-1, 1] and k is a solution in the nearness of *i*).
5: Insert the greedy selection process between xi and υi.
6: Evaluate the probability rate Pi for the solutions xi depending on the fitness amount using:

$$P_i = \frac{\mathrm{fit_i}}{\sum_{\mathrm{i=1}}^{\mathrm{SN}} \mathrm{fit_i}} \tag{4}$$

The fitness values fit calculated as the following:

$$\mathrm{fit_i} = \begin{cases} \frac{1}{1+\mathrm{f_i}} & \text{if } \mathrm{f_i} \geq 0 \\ 1 + abs(f_i) & if \ \ f_i < 0 \end{cases} \tag{5}$$

The P_i value is between [0, 1].
7: Find the new solutions for the onlookers (new positions) $\mathrm{V_i}$from the solutions$\mathrm{X_i}$. The selection depends on Pi and calculates them.
8: apply the greedy selection between $\mathrm{X_i}$ and $\mathrm{V_i}$ for the onlookers.
9: Find the abandoned food (source) and if exists, exchange it with a randomly generated solution $\mathrm{X_i}$ for the scout using the equation

$$X_{i,j} = minj + rand\ (0,1) * (maxj - minj) \tag{6}$$

10: Remember the suitable food source position (solution) gained so far.
11: *Cycle = cycle + 1*
12: IF (cycle= Maximum Cycle Number (MCN)) then GO to step 4.
13: END.

Control parameters of BCO Algorithm

The control parameters that used in this work for BCO algorithm to find optimum parameters setting of PI controller as follows:

NP=20; The number of colony size = (employed bees + onlooker bees).
Onlookers Number = 50% of the swarm.
Employed bees Number = 50% of the swarm.
Scouts number =1.
Food Number = NP/2; The food sources number equal to the half colony size.
Max Cycle = 100; The stopping criteria of foraging.
D = 12; The problem parameters to be optimized.
Limit = Food Number * D; A food source is left by its employed bee when it not be enhanced by the "limit" trials.
A program in MATLAB is built with the BCO optimization technique as shown in the flowchart of Fig. 11.

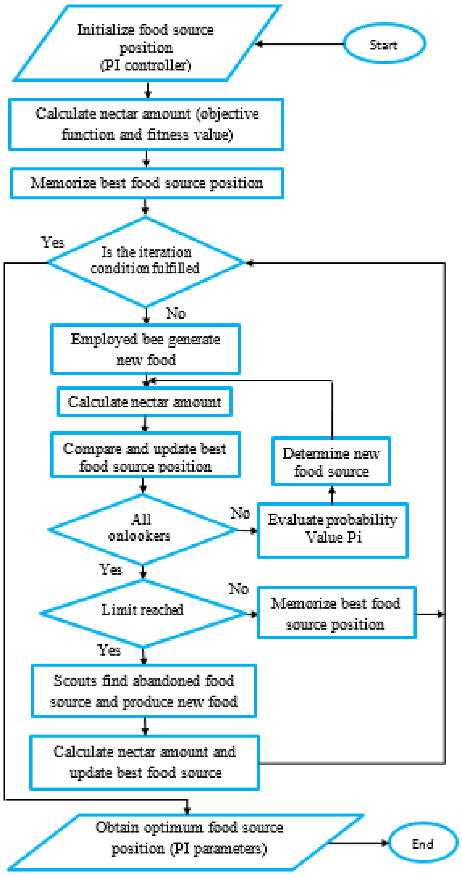

Fig. 11 Flowchart of bee colony optimization

Case Study and Simulation Results

A. Cases Study

Doubly Fed Induction Generator (DFIG) connected to Iraqi network has been simulated by using MATLAB software which provides an excellent representation of the system. Three types of faults have been implemented at the terminal of wind generator namely; Single Line to Ground fault (SLG), Double Line to Ground fault (DLG), and Three Line to Ground fault (TLG).

Two methods for reducing the overshoot fault current with DFIG have been analyzed and compared during this work:

1- Using conventional PI controller based on trial and error.
2- Using Intelligent PI controller based on BCO technique.

In each application, the faults are applied in this work on the terminal of the wind generator when:

1- Wind speed is fixed (14 m/s).
2- Wind speed is varied (8 to 14 m/s).

Figure (12) shows the main steps of the proposed work.

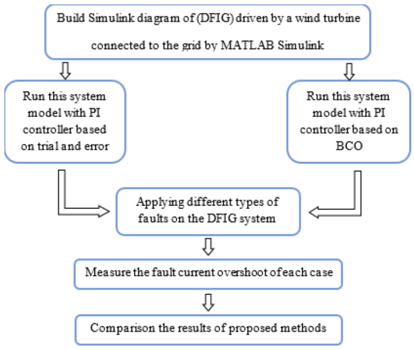

Fig. 12 Block diagram of the main steps of proposed work

B. Simulation Results of Doubly Fed Induction Generator (DFIG) with PI controller

Trial and error method is one of tuning the methods used for conventional PI controller gains tuning. Table (4.1) illustrates the initial values of PI controller gains give a minimum overshoot fault current.

Table 1: PI controller parameters of trial and error method

PI Controller	Voltage regulator gains		Power regulator gains		Rotor-side convertor current gains		Grid-side convertor current regulator gains	
PI Parameters	K_{p1}	K_{i1}	K_{p2}	K_{i2}	K_{p3}	K_{i3}	K_{p4}	K_{i4}
Initial design	1.25	300	1	100	0.3	8	1	100

The current response of wind turbine system of Fig. 13 in normal condition and the responses after applying various types of faults at bus 400V are shown in Figures (14 to 19).

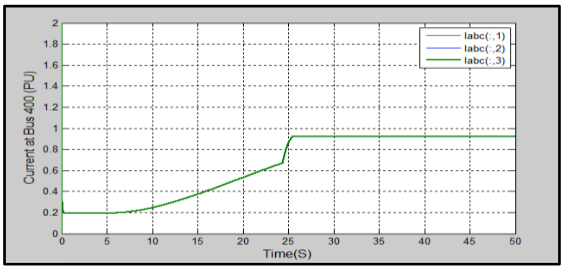

Fig. 13 Three phase currents at bus B400 for normal operating condition

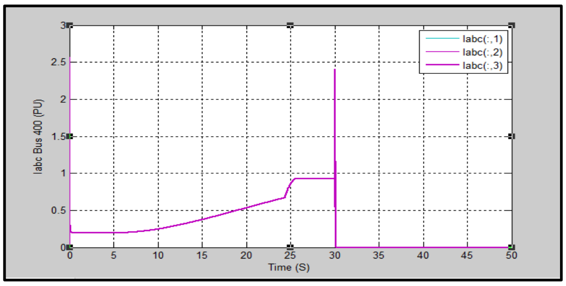

Fig. 14 Three phase currents at bus B400 with single line to ground fault at fixed wind speed

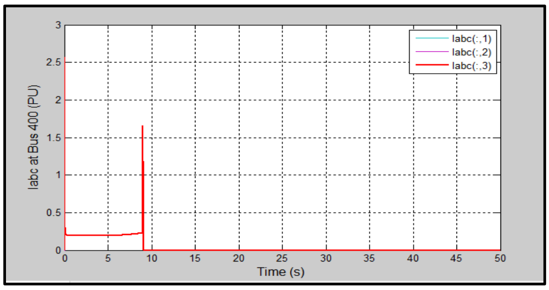

Fig. 15 Three phase currents at bus B400 with single line to ground fault at variable wind speed

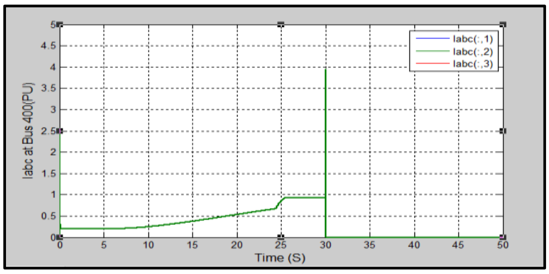

Fig. 16 Three phase currents at bus B400 with double lines to ground fault at fixed wind speed

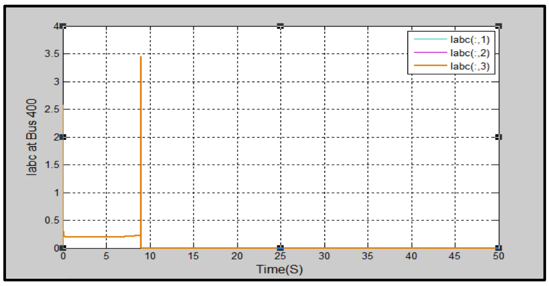

Fig.17 Three phase currents at bus B400 with double lines to ground fault at variable wind speed

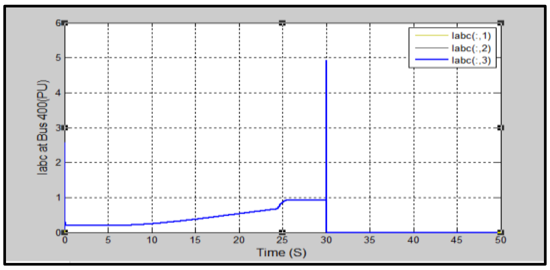

Fig. 18 Three phase currents at bus B400 with three lines to ground fault at fixed wind speed

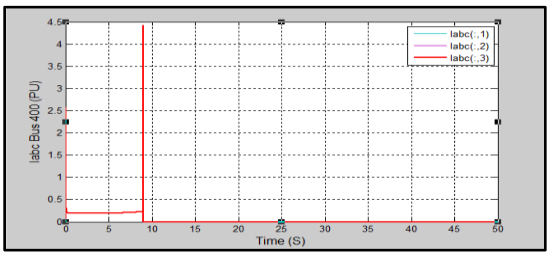

Fig. 19 Three phase currents at bus B400 with three lines to ground fault at variable wind speed

C. Simulation Results of DFIG with PI controller based on BCO technique

Bee Colony Optimization (BCO) is one of the newest methods in the optimization techniques used in this work in order to provide a better PI controller and less overshoot fault current by finding the optimum parameter gains of PI controller. The optimal PI-controller gains tuned by BCO method are illustrated in Table 2 after applying the BCO tuning algorithm flowchart of Fig. 11.

Table 2 PI parameters using BCO technique.

PI Controller	Voltage regulator gains		Power regulator gains		Rotor-side convertor current gains		Grid-side convertor current regulator gains	
PI Parameters	K_{p1}	K_{i1}	K_{p2}	K_{i2}	K_{p3}	K_{i3}	K_{p4}	K_{i4}
PI-BCO Parameters	1.182	4.046	3.743	0.6009	2.732	8.424	2.625	1.629

The size of population used in BCO is 10 and the number of iterations is 6 iterations. All the previous cases are repeated in section B but with the new tuning parameters in Table 2, the overshoot fault current is calculated as follows:

Case 1: Turbine response under single line to ground fault at fixed wind speed using BCO parameters

A single line to ground fault is applied to bus B400 (terminal of generators) of power system in Fig. 6 at time 30 sec. and lasts for 0.2 sec. with a fixed wind speed at 14 m/s, when use BCO parameters for PI controller. The value of the current reaches to 1.8 (pu) which is less than the value of overshoot fault current by using the traditional PI controller by 25%. Fig. 20 shows the response of phase current at bus B400.

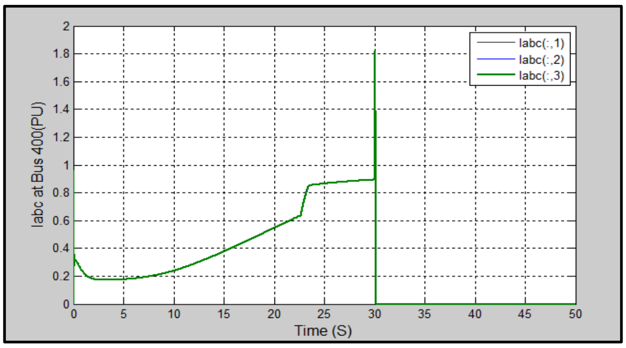

Fig. 20 Three phase current at bus 400 with single line to ground fault at fixed wind speed using BCO parameters

Case 2: Turbine response under single line to ground fault at variable wind speed using BCO parameters

A Single line to ground fault is applied to a terminal of generators at time 9 sec and lasts for 0.2 sec for the same power system of case 1 when using BCO parameters for PI controller and applying variable wind speed from 8m/s to 14m/s. The value of current increases to 1.18 (pu) (this value is less than using traditional PI by 28.48%). The phase current response is shown in Fig. 21.

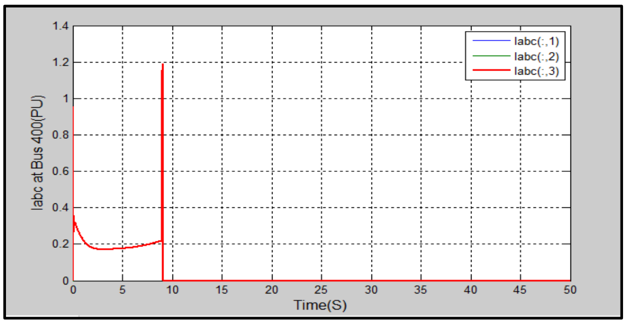

Fig. 21 Three phase currents at bus B400 with single line to ground fault at variable wind speed using BCO parameters

Case 3: Turbine response under double lines to ground fault at fixed wind speed using BCO parameters

A double line to ground fault is applied to a terminal of generators at time 30 sec. and lasts for 0.2 sec. by using BCO method for optimizing the parameters of PI controller. For the same power system of Fig. 6 and the wind speed is fixed to 14 m/s, the value of overshoot fault current is 2.06 pu. Fig. 22 shows the response of phase current at bus B400.

Based on the current response, by using the BCO, the fault current has been reduced by 47.84% as compared to the fault current in case of using PI controller only, that is because the BCO produces an optimized value to the PI parameters of the PI controller.

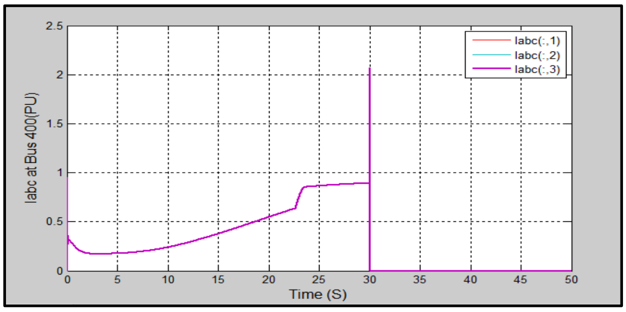

Fig. 22: Three phase currents at bus B400 with double lines to ground fault at fixed wind speed using BCO.

Case 4: Turbine response under double lines to ground fault at variable wind speed with BCO parameters

When double lines to ground fault are applied to a terminal of generators at time 9 sec. and lasts for 0.2

sec. when using BCO method with variable wind speed the value of the fault current is 1.9 pu which is less by 44.9% than using traditional PI controller. Fig. 23 shows the response of phase current at bus B400 of Fig. 6.

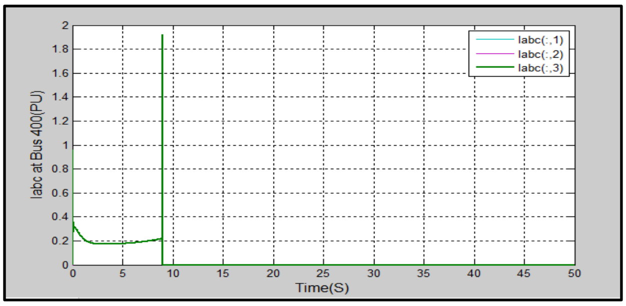

Fig. 23 Three phase currents at bus B400 with double lines to ground fault at variable wind speed using BCO.

Case 5: Turbine response under three lines to ground fault at fixed wind speed with BCO parameters

Three lines to ground fault are applied to a terminal of generators at time 30 sec. and lasts for 0.2 sec. with a fixed wind speed 14 m/s, with BCO parameter of controller, the value of the overshoot current is 2.4 pu. Fig. 24 shows the response of phase current according to this case on bus B400 (terminal generator) of Fig. 6.

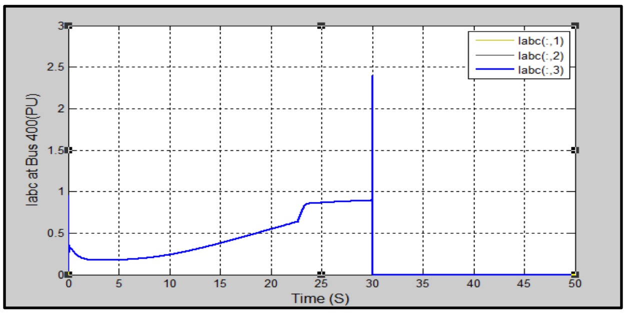

Fig. 24 Three phase currents at bus B400 with three lines to ground fault at fixed wind speed using BCO.

Based on the above results, the overshoot fault current by using BCO is much less than using the traditional PI only by 51.3%.

Case 6: Turbine response to a three line-ground fault at variable speed with BCO parameters.

When three lines to ground fault are applied to a terminal of generators at time 9 sec. and lasts for 0.2 sec. with a variable wind speed from 8 m/s to 14 m/s, when using BCO parameter of controller, the value of the current is 1.45 pu which is much less than the overshoot fault current by using traditional PI controller by 67.1%. Fig. 25 shows the response of phase current according to this case on bus B400.

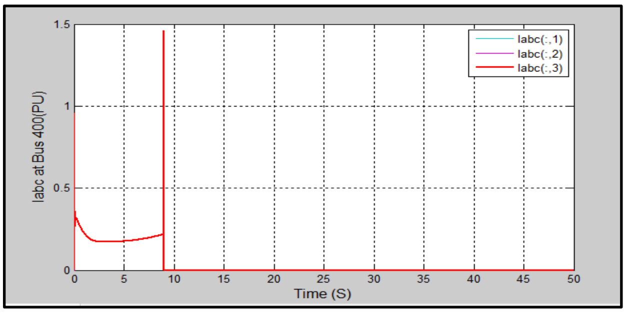

Fig. 25 Three phase currents at bus B400 with three lines to ground fault at variable wind speed using BCO.

Comparison Study between Traditional PI and PI Based BCO

PI controller has been used during this work in order to reduce the system overshoot fault current when different type of faults accrued. PI controller is used in four controllers of DFIG wind system namely, rotor side convertor voltage control, rotor side convertor current control, rotor side convertor power control and grid side power convertor current control as shown in Figures 7 to 10. In order to increase the reliability of the PI controller and to reduce the overshoot current, it is required to find the optimal parameters of the PI controller. Bee Colony Optimization (BCO) is used to find the optimal parameters of PI controller Table 3 illustrates the minimum overshoot current after using PI tuned with BCO.

Table 3 Overshoot current value tuned by PI controller for different optimization techniques

	Fault type	Overshoot current tuned by PI	Overshoot current tuned by PI-BCO
Fixed speed	**SLG fault**	2.4 pu	1.8 pu
	DLG fault	3.95 pu	2.06 pu
	3LG fault	4.93 pu	2.4 pu
Variable speed	**SLG fault**	1.65 pu	1.18 pu
	DLG fault	3.45 pu	1.9 pu
	3LG fault	4.42 pu	1.45 pu

According to the above results, it can be noted that the average reduction of overshoot current by using PI-BCO is 44.12% than using the PI controller only. Therefore, PI-BCO controller is selected in this work to be the optimal solution to reduce the overshoot current.

Conclusions

In this work a complete description of an optimal PI controller parameter design of wind energy system connected to a system similar to national Iraqi network in voltage level and frequency has been proposed and presented. Intelligent technique has been used in order to control the current, power and voltage of the system during normal and abnormal conditions. The main conclusions that can be extracted from this proposed work can be summarized as follows:

1) The conventional PI controller based on trial and error in finding the parameters in such a wind system does not assure good tuning results and in some cases, produce a steady state error and higher overshoot current during the fault.
2) Due to the high complexity and nonlinearity of the system, the optimal parameters of PI controller are difficult to find out by using conventional PI controller with traditional method. So, the PI controller based intelligent techniques is used instead of the optimal performance.
3) The intelligent algorithm technique is more efficient and accurate than the conventional algorithm in finding the optimum parameter design of PI controller to enhance the wind system performance.
4) Three-lines to Ground fault (TLG) are the most dangerous fault types than the others (SLG and DLG) that badly affect the wind system because they produce a high value of overshoot fault current than the others by 35.5% as an average.
5) The average reduction of overshoot fault current by using the intelligent technique PI-BCO is 44.12% than using the conventional PI controller only as illustrated in Table 3.
6) The PI – BCO technique during this work is chosen to be the ideal solution for finding the optimal parameter design of PI controller.
7) The proposed intelligent controller with the optimization algorithm used in this work is suitable for different types of wind systems and it is a general algorithm which can be accommodated easily when needed.

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