

Controller Design of DFIG Based Wind Turbine by Using Evolutionary Soft Computational Techniques

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Abstract—This manuscript illustrates the controller design for a doubly fed induction generator based variable speed wind turbine by using a bioinspired scheme. This methodology is based on exploiting two proficient swarm intelligence based evolutionary soft computational procedures. The particle swarm optimization (PSO) and bacterial foraging optimization (BFO) techniques are employed to design the controller intended for small damping plant of the DFIG. Wind energy overview and DFIG operating principle along with the equivalent circuit model is adequately discussed in this paper. The controller design for DFIG based WECS using PSO and BFO are described comparatively in detail. The responses of the DFIG system regarding terminal voltage, current, active-reactive power, and DC-Link voltage have slightly improved with the evolutionary soft computational procedure. Lastly, the obtained output is equated with a standard technique for performance improvement of DFIG based wind energy conversion system.

Keywords—DFIG; Wind turbine; PID controller; Matlab; Simulink; model; PSO; BFO; Fitness; function

Abbreviations:

DFIG: Doubly Fed Induction Generator
PID: Proportional Integral Derivative
PSO: Particle Swarm Optimization
BFO: Bacterial Foraging Optimization
WECS: Wind Energy Conversion Systems
WRSG: Wound rotor synchronous generator
PMSG: Permanent magnet synchronous generator
SCIG: Singly excited induction generator.

I. INTRODUCTION

Wind power is considered probably the optimum available renewable energy sources and has widely developed in recent years due to its advantages such as low pollution, comparatively low capital cost involved and the short gestation period [1]. There have been several types of generators for wind energy conversion configuration. The older approach involved synchronous generators whereas the recent approach focuses more on induction generators of different types [2]. Simple induction generators have a few weaknesses such as reactive power utilization and unregulated voltage profile during variable rotor speed. These problems can be solved by employing power electronic converter or regulators. The DFIG

is a wound rotor induction machine that can operate in super-synchronous and sub-synchronous manner. The benefits of the DFIG as compared with fixed speed generators are that they improve power quality, reduce mechanical stress and fluctuations and exhibit excellent power imprints [3]. The function of the DFIG associated with the grid is facilitated through a rotor as well as a network side converter. However, an inverter related to the rotor side is used to provide give a fundamental frequency to sustain stator frequency at an invariable stage, despite the variations in mechanical power. The control of DFIG presents a dual dilemma: to balance the velocity changes and reactive power. In reality, DFIGs should be cut off from the network while the voltage inequity is more than 6% [3]. It has been described that the torque pulsation could be concentrated by using injected recompense current in the DFIG rotor. In [4], authors presented a relevant study of a simplified model, in which the authors compare the fifth plus third order model of DFIG followed using the investigation under faulted circumstances. However, in [5], authors offered magnitude along with frequency control of network associated DFIG based on a coordinated model for wind power production [5]. The numerical differentiation based additive model approximately the nominal working position of DFIG was used. The effectiveness of such type models can be validated from the outcomes offered. The ranking of wind turbines from 800kW to 3 MW but wind farm assortment is 2MW to 200MW [7]. In this paper, we provide an alternate technique to design a controller for the DFIG system considered by [7, 8] using two bioinspired techniques. The obtained results are compared with existing solutions. The implementation of DFIG for voltage regulation at a remote location has been described in a previous work [21].

The global trend toward clean energy is an inspiration for more integration of wind-based electrical energy in power systems [9]. Vast and small wind turbines produce electrical energy for networks whereas they sustain stand-alone isolated areas like well [10]. However, the wind velocity changes radically depending on the environmental circumstances along with the time of operation. Therefore, there is a huge margin of speed difference. Such margins of speed alteration make the wound rotor induction machines appropriate for power

generation through wind energy [11]. Wind turbines can run either at fixed speed (actually within a speed range about 1 %) or at varying speed [12]. For fixed speed wind turbines, induction generator is instantly coupled to the grid. Hence, for a fixed-speed system, the turbulence of the wind will result in power fluctuations, which influence power quality. Power electronic apparatus are used to control the DFIG based variable-speed wind turbine. DFIG based wind turbine aerodynamics has thoroughly been described in [13-16, 17].

II. GENERAL IDEA AND WORKING PRINCIPLE OF DFIG

A part of wound rotor induction generators, also known as DFIG, is one of the most frequently used scheme in the wind energy industries [18]. Currently, these types of generators are extensively accepted as one of the appropriate wind energy conversion systems. DFIG is in nature a wound rotor induction generator, and the rotor circuit is usually controlled by electric power devices to allow variable speed operation. DFIG stator winding associated directly to the grid by a power transformer and DFIG's power is usually ranged from a few kilowatts to several megawatts. The size for a rotor converter is about 30% of a full capacity converter. During low wind speed, more electrical energy could be acquired from a variable speed DFIG, in distinguishing with a fixed speed wind generator [2]. The advantages of using DFIG in WECS is described in [2]. Whereas in [19] DFIGs have two operating modes, in (i) mode $N_r > N_s$, S is $-ve$, then generator in super-synchronous mode and both stators, as well as rotor windings, deliver power to the grid. while in (ii) mode $N_r < N_s$, s is $+ve$ the generator in subsynchronous mode and stator winding delivers power to both the grid and the rotor winding. The mathematical modeling of DFIG is thoroughly explained in [20]. The machine data is available in per unit reactance form. A DFIG equivalent circuit can be seen in [21]. The sixth order relations for unbalanced operations, is as follows [7, 8]:

$$G(S) = \frac{0.000324s^6 - 1.75s^5 - 2366s^4 + 7.9e6s^3 + 7.5e9s^2 + 5e12s + 2.18e14}{s^6 + 2340s^5 + 8.67e6s^4 + 4.79e9s^3 + 2.7e12s^2 + 1.27e14s + 9.6e14}$$

III. PARTICLE SWARM OPTIMIZATION

An overview and brief description for particle swarm optimization along with algorithm features is given in [22-28]. This approach is appropriate to solve nonlinear problems and is established on flock activities such as birds detect food using gathering. The first alternative of the PSO algorithm brings using having the inhabitants (named the swarm) for the applicant result (known as particles). These particles are turned in the search space using a few straightforward formulas. The motions of the particles are guided to their best-known position in the search space in addition to the entire swarm's most prestigious situation. Whenever an enhanced position is being detected, then it will move towards to guide the movement of the flock. The procedure is repetitive, furthermore using performing, so it is trusted, but not assured, that an adequate result will finally be detected. Here in this procedure, a set of particles is introduced in the d-dimensional search space using at random selecting velocity as well as position. The first situation of the particle is considered as the best place to initiate, as well as the velocity of the particle is updated based

on experience to the other particles from the swarming population.

A. A minute representation for the algorithm

We set the values of PSO algorithm constants as inertia weight factor $W = 0.3$, along with acceleration constants $C_1, C_2 = 1.5$. As we have to optimize three parameters that are; K_p, K_D, K_I to the controller, and search optimal value in the three-dimensional search space. So we arbitrarily formatted a swarm of "100" population in three-dimensional search space using $[X_{i,1} X_{i,2} X_{i,3}]$ and $[V_{i,1} V_{i,2} V_{i,3}]$ as preliminary situation as well as velocity. Considered primary fitness function of each point along with the position with minimum fitness function is exhibited as g_{best} (initial value of global best Optima) as well as the optimal fitness function as f_{best1} (Initial best fitness function). We ran the program by means of PSO algorithm through thousands (or yet additional numbers) of iterations; in addition to program brought back the final optimal value of fitness function as " f_{best} " along with last global optimum point as " G_{best} ."

B. The conception of fitness function to the controller design

For best results we optimize all PID parameters, of the and describe a three-dimensional search space in which all three dimensions present. Every precise point in search space accounts for a particular arrangement of $[K_p, K_I$ and $K_D]$. For which an appropriate answer has found, and a fitness function determines the performance of the position to the PID parameters. This fitness function comprises numerous essential features to the performance index for design. Along with the best position in search space, the fitness function reaches an optimal value with four essential functions which defined fitness function. By this function; steady state errors, peak overshoot, rise time as well as settling time has been come out for the defined system. The contribution of these essential functions towards the innovative fitness function is determined by a scale factor. At best position fitness function has minimal value. The chosen fitness function is defined as follows:

$$F = (1 - \text{EXP}(-\beta)) (M_p + E_{ss}) + (\text{EXP}(-\beta)) (T_s - T_r)$$

Here F : Fitness function, M_p : Peak Overshoot, T_s : Settling Time, T_r : Rise Time, β : Scaling Factor (Depends on upon the alternative of the designer), scaling factor $\beta = 1$. In the Matlab library, we have to define a fitness function which has PID parameters as input values, as well as it returns fitness value of the PID based controller model as output and formatted as follows. The Function $[F] = \text{fitness}(K_D, K_p, K_I)$

C. PSO based controller gain

The PSO based controller gains for the 6th order transfer function reduced the model to the DFIG system, at best fitness function ($f_{best}=0.1967$) by several iterations which are given in Table I.

TABLE I. GAINS OF THE PSO-BASED CONTROLLER

Gbest Parameters	K_p	K_I	K_D
Gains	39.9781	7.6902	0.0271

IV. BACTERIAL FORAGING OPTIMIZATION

A. Description

A description for bacterial foraging optimization with algorithmic features is given [29-33]. The algorithm is heavily based on the behavior of E.colli bacteria. In the bacterial foraging optimization process four mobile behaviors are mimicked:

1) Chemotaxis:

A chemotactic step can be defined as a tumble followed by a tumble or a tumble a run lifetime. To represent a tumble a unit length random direction, X (j), is generated; this will be used to describe the direction of movement after a tumble. In particular :

$$X^{i(j+1,k,l)} = X^{i(j,k,l)} + C(i) * X(j) ,$$

Where $X^{i(j,k,l)}$ represents the i^{th} bacterium at j^{th} chemotactic, k^{th} reproductive as well as l^{th} elimination and dispersal step. $C(i)$ is the size of the step taken in the random direction specified by a tumble(the run length unit).

2) Swarming:

E.Colli cells can work cooperatively self-organize into highly structured colonies with high environmental adaptability using a complex communication means. Overall, cells provide an attraction signal to each other, so they swarm together. The mathematical representation for swarming can be represented by:

$$J_{cc}(\theta, P(j,k,l)) = \sum^j cc(\theta, \theta^i(j,k,l)) = \sum [D_{attract} * EXP(-W_{attract} * \sum(\theta_m - \theta^i m)^2)] + \sum [H_{repellant} * EXP(-W_{repellant} * \sum(\theta_m - \theta^i m)^2)]$$

Where $J_{cc}(\theta, P(j,k,l))$ is the cost function value to be additional to the actual cost function, that is to be minimized to present a time-varying cost function. S is the total number of bacteria , P is the number of parameters to be optimized which are present in each bacterium and $D_{attract}$, $W_{attract}$, $H_{repellant}$, $W_{repellant}$ are different coefficients that should be appropriately chosen.

3) Reproduction:

The least healthier bacteria die with the other each healthier bacteria split into two novel bacteria each placed in the similar position.

4) Elimination and Dispersal:

It is probable that in the local surroundings, the lives of a population of bacteria changes either gradually (e.g., via utilization of nutrients) or abruptly due to some other influence. Events can occur that all the bacteria in a region are killed, or a group is dispersed into a new part of the environment. They have the effect of possibly destroying the chemotactic progress.

B. BFO based controller gain

The BFO algorithm process as a flowchart is given in [33]. The BFO based controller gains for the 6th order Transfer function reduced the model to the DFIG system, at the fitness function (function F = Fitness ($K_D K_P K_I$)) by several iterations which are given in Table II.

TABLE II. GAINS OF THE BFO-BASED CONTROLLER

Parameters	K_p	K_i	K_d
Gains	0.1417	0.1472	0.1005

V. SIMULATION AND RESULTS

A. Simulink response of the DFIG system

Here Wind Farm - DFIG Average Model (MATLAB 13b) shows a 9 MW wind farm with the DFIG driven by a variable speed wind turbine. It consisted of six 1.5 MW wind turbines and linked toward a 25 kV distribution system exports power to a 120 kV grid through a 30 km, 25 kV feeder. In this illustration, the wind velocity is preserved invariable at 15 m/s. The response of the DFIG based wind turbine with the evolutionary soft computational procedure (PSO-based controller) regarding voltage along with current at the terminals, active power generated; reactive power requirements and DC capacitor voltage in Pu are shown in Figures 1 and 2 respectively. AS shown, the response of the DFIG system regarding terminal voltage, current, active-reactive power and DC-Link voltage has slightly improved with the PSO based controller compared to the BFO based controller.

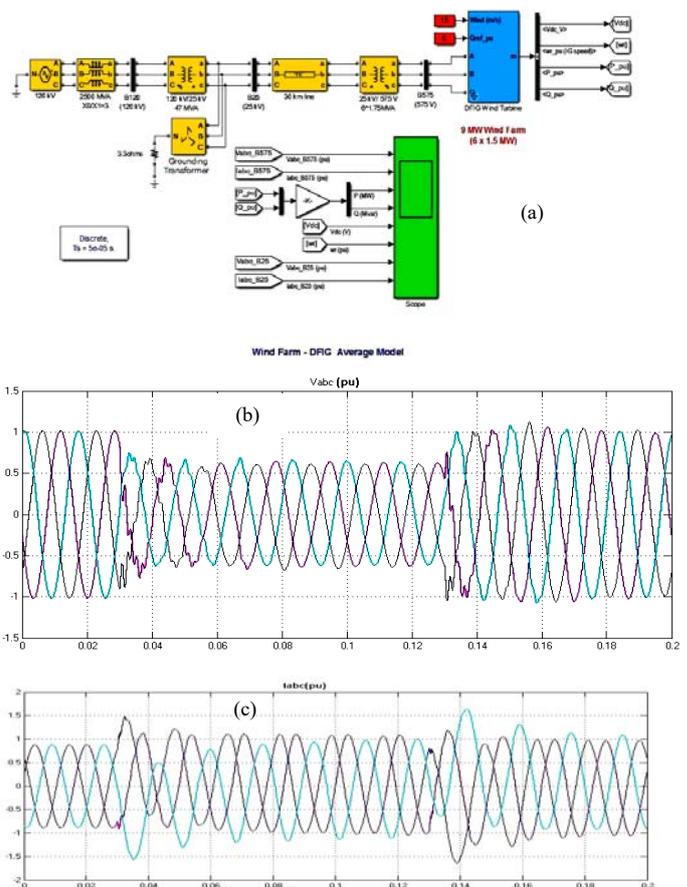


Fig. 1. (a) DFIG based wind turbine Average Matlab Simulink Model diagram, (b) Voltages at the DFIG terminals in Pu, (c) Currents at the DFIG terminals in Pu

B. BFO based Control Response by PID Controller

The reaction of the BFO based PID controller is given in [7, 8]. As shown the system has zero undershoot in the response of open loop system. The step response of the BFO based PID-controller is shown in Figure 3 and Table III.

C. Response of PID Controller Using PSO Method

The step response of the PSO based system is given in Figure 4. It is observable by a comparison result of BFO based PID control along with one describe in this work which shows that; PSO based PID controller has extended to sufficiently damped BFO based controller without compromising the speed of response to the control loop. Now the step response of open as well as close loop reduced order system by PID controller with the PSO technique is shown in Figure 4 and Table IV.

D. Comparison between BFO based PID controller and PID-controller using PSO method

By comparing Tables III and IV the following observations can be made:

- The designed PSO based PID controller can reduce the steady state error to zero as the existing one.
- The rise time, peak time and overshoot have been reduced to zero, and the response is no more underdamped.
- The speed response is much better than that of the current controller. Hence intended controller in this paper assists to eliminate reactive power variations in DFIG system.

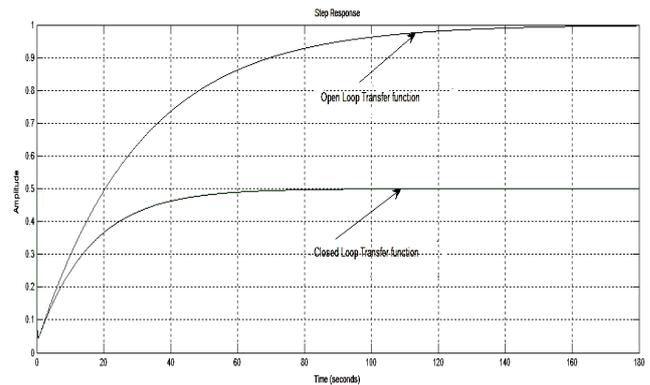


Fig. 3. Step response of the BFO based PID controller

TABLE III. STEP RESPONSE OF BFO BASED PID CONTROLLER

Rise Time	Settling Time	Settling Min	Settling Max	Over Shoot	Under Shoot	Peak	Peak Time
0.00 sec	62.3541 sec	0.0438 sec	0.4992 sec	0.0 %	0.0 %	0.500	0.0 sec

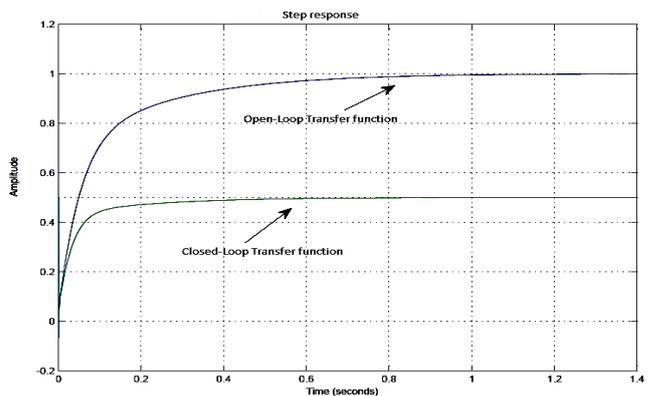


Fig. 4. Step response of the PSO-based PID controller

TABLE IV. STEP RESPONSE OF THE PSO-BASED PID CONTROLLER

Rise Time	Settling Time	Settling Min	Settling Max	Over Shoot	Under Shoot	Peak	Peak Time
0 sec	0.4061 sec	-0.0694 sec	0.4996 sec	0 %	13.8754%	0.50	0 sec

VI. CONCLUSION

The BFO based PID controller improves system responses in comparison with an open loop system, while the PSO based designed controller not only improves the system response but also reduces the percentage overshoot to zero. The obtained outcome demonstrates that the system using PSO based controller settles down in less time compared to the BFO based PID controller scheme. The comparison between the PSO based controller and the BFO based PID controller is discussed. It is accomplished that the settling time is condensed next to near about 62% along with the percentage overshoot; rise time and peak time are reduced to zero. Finally, it is fulfilled that PSO based control technique afford another alternative to

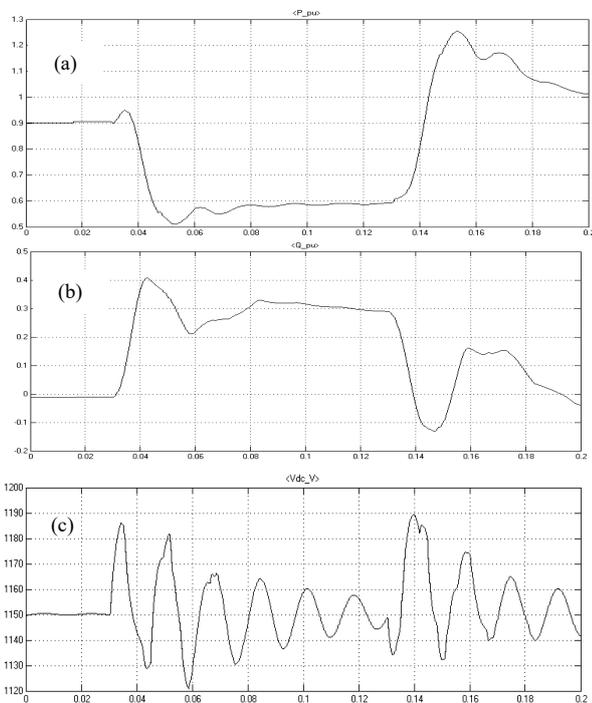


Fig. 2. (a) Active power delivered of the DFIG in Pu (b) Reactive power requirement of the DFIG in Pu (c) DC link voltage at the ordinary linkage capacitor

propose a reliable and adequate controller to the DFIG based wind energy conversion systems.

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Appendix: DFIG Simulation Data

Base values: $S_b = 2 \text{ MVA}$, $V_b = 690 \text{ V}$, $\omega_b = 2\pi f$ (rad/s), $f = 60 \text{ Hz}$,

$Z_{dc} = V_{dc}/I_{dc}$, $I_b = 1900 \text{ A}$, $V_{dc} = 1150 \text{ V}$, $Z_b = (V_b/\sqrt{3})/I_b$, $L_b = Z_b/\omega_b$,

$L_{dc} = Z_{dc}/\omega_b$, $C_b = 1/(Z_b \omega_b)$, $T_b = S_b/\omega_b$, $J_b = S_b/(\omega_b^2)$, $I_{dc} = S_b/Y_{dc}$,

$C_{dc} = 1/(Z_{dc} \omega_b)$, Infinite bus voltage (Pu): $V_{dq, inf} = [0.989 \quad 0.15]$

DFIG (Pu): $R_s = 0.023$, $R_r = 0.016$, $L_s = 0.180$, $L_r = 0.16$,

$L_m = 2.9$, DC link component: $v_{dc}^{ref} = 1$, $C_{dc} = 12.7227$

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