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IMPROVEMENT THE DFIG ACTIVE POWER WITH VARIABLE SPEED WIND USING PARTICLE SWARM OPTIMIZATION

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ABSTRACT: - The Wind Energy Conversion System (WECS) has become very popular and more attractive to study the possibility of replacing the conventional power source by renewable energy. This paper is focusing on the modeling and analysis of (DFIG) in Matlab/Smulink with constant and variable speed wind. Three test systems are considered and implemented. The first system is studied with constant wind speed using sinusoidal pulse width modulation (SPWM) to control the switching of two level three phase back to back converters. The second system is investigated also with constant wind speed but using space vector pulse width modulation (SVPWM). The two systems have been simulated and the results shows the effect of each type of pulse width modulation.

Two fault conditions are subjected to the second system, single line to ground fault at phase A (in 33KV line), programmable fault (three phase voltage drop to 0.5pu) at the Grid bus (132KV bus). Then the system recovery at the steady-state under faults is shown.

For the third system the input was the variable speed wind, the simulation results illustrate that when the input is variable wind speed the generated power will be reduced and the system behavior unstable, therefore, the control circuit is needed for the optimization to reduce the losses of the generated power; this optimization can be made by tuning the controllers gains with new suitable values, so the optimization is made by using Particle Swarm Optimization (PSO).

The new optimal values improved the system behavior, and illustrated the possibility of operation with variable wind speed.
***Key words**: Wind, Turbine Generator, Doubly Fed Induction Generator (DFIG), Variable Wind Speed, Particle Swarm Optimization (PSO).*

1. INTRODUCTION

The last 10 years has seen the evolution in the use of wind energy, which is one of the most important sources of renewable energy, which entered the field of actual work, especially in some countries where more than 70% of clean energy sources have been installed in it countries. Expected that the percentage use of renewable energy reached to 20% in 2020 and the wind power is expected to the largest share of this percentage from the fields of wind turbines, especially in areas near the sea, where the rate of these fields will generate (2-3 GW) from power the researcher of power field are planning to increase these fields to reach the generation capacity at (20-25 GW) in 2030(1).

Wind turbines can be divided into two main types relative to the axis of rotation (Vertical & horizontal turbines). Also there are three types of generators used in wind turbines. The three types are including (squirrel cage induction generators, synchronous generators and doubly fed induction generators (DFIG)). The first type was used in the old turbines, which is directly linked to the generator and turbine. This type is called a fixed speed turbine. Turbines mage watts are called for the second & third types of turbine in the modern or so. These turbines are working with velocities changing where it linked to the generator via the network, (these turbines to mechanical stress is less of a change in wind speed where the router absorb these changes in the velocities of any will work there and thus stores energy temporarily)[2].

For a variable speed wind turbines the generator is controlled by power electronic equipment. There are several reasons for using variable-speed operation of wind turbines, among those are possibilities to reduce stresses of the mechanical structure, acoustic noise reduction and the possibility to control active and reactive power [1, 2]. The rotor windings and variable-speed operation are obtained by injecting a controllable voltage into the rotor at the desired slip frequency. The rotor winding is fed through a variable-frequency power converter, typically based on two (AC/DC/AC) IGBT-based voltage source converters (VSCs), linked through a DC bus. The variable-frequency rotor supplies from the converter which enabled the rotor mechanical speed to be decoupled from the synchronous frequency of the electrical network, thereby allowing variable-speed operation of the wind turbine [2, 3].

2- WIND ENERGY CONVERSION SYSTEM WITH CONCEPT OF DOUBLY FED INDUCTION GENERATOR (DFIG):

The DFIG which is gradually growing as a technology for variable rotational speed wind turbine. DFIG topology offers several advantages in comparison to systems using direct-in-line converters. A (DFIG) is basically a standard, Wound Rotor Induction Machine which its stator windings directly connected to the grid and its rotor windings connected to the grid through a converters[3].

DFIG topology offers a decoupled control of generator active and reactive powers. The cost and size of the inverter can be reduced since the inverter size is reduced. In addition, the inverter harmonics are lowered since the inverter is not connected to the main stator windings [2, 3]. As shown in Figure (1).

3- WIND TURBINE POWER CHARACTERISTICS FOR VARIABLE SPEED WIND

Wind turbine converts the wind energy to mechanical energy rotating generator. The following well-known algebraic equation gives the relation between wind speed and mechanical power extracted from the wind [1, 2].

$$P = \frac{1}{2}\rho A V_w^3 C_p \qquad \text{(Watt)} \qquad \ldots (1)$$

Where (ρ) is the air density [kg/m^3], (A) is the area covered by the rotor blades, and (V_w) is the wind speed and (C_p) is the turbine power coefficient as shown in equation (2) which is the function of the tip speed ratio (λ) and pitch angle (β), (angle of incidence of the blade and the wind direction).
Where:

$$C_p = \frac{\text{Rotor power}}{\text{Power in the wind}} = \frac{P_{rotor}}{\frac{1}{2}\rho A U^3} \qquad \ldots (2)$$

Equation (3) describes the rotor of constant-speed and variable-speed wind turbines [1, 4, 5]:

$$C_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\beta^{c_5} - c_6\right)\exp\left(\frac{-c_7}{\lambda_i}\right) \qquad \ldots (3)$$

Where

$$\lambda_i = \left[\left(\frac{1}{\lambda + c_8\beta}\right) - \left(\frac{c_9}{\beta^3 + 1}\right)\right]^{-1} \quad \ldots(4)$$

The values of the constants c_1 to c_9 in Table (1) have been changed slightly in order to match the manufacturer data better. Figure (2) illustrate the characteristics of C_P with wind speed [1, 3].

At variable speed wind typical power curves which are a function of the wind speed and the turbine angular speed are illustrated in Figure (3). Note that at every wind speed there is an optimum turbine speed at which the power extraction from the wind is maximized [4].

4- MATHEMATICAL MODEL OF DFIG:

Figure (4-A-B) shows a typical equivalent circuits of mathematical model of (DFIG) which shows a standard, wound rotor induction machine. The AC/DC/AC Converter is divided into two components: the rotor side converter (RSC) and the grid side converter (GSC) as shown in Figure (1) [1, 5].

For a doubly fed induction machine as in Figures (4-A-B) and the Park transformation's application to the traditional a, b, c model allows to write a dynamic model in a d-q reference frame as follows[6,7,8]:

$$V_{ds} = R_s I_{ds} + \frac{d}{d_t}\psi_{ds} - \omega_s \psi_{qs} \quad \ldots(5)$$

$$V_{qs} = R_s I_{qs} + \frac{d}{d_t}\psi_{qs} + \omega_s \psi_{ds} \quad \ldots(6)$$

$$V_{dr} = R_r I_{dr} + \frac{d}{d_t}\psi_{dr} - (\omega_s - \omega_r)\psi_{qr} \quad \ldots(7)$$

$$V_{qr} = R_r I_{qr} + \frac{d}{d_t}\psi_{qr} + (\omega_s - \omega_r)\psi_{dr} \quad \ldots(8)$$

WhereV_{ds}, V_{qs}, V_{dr} and V_{qr} are the q-axis and d-axis stator and rotor voltages, respectively. I_{ds}, I_{qs}, I_{dr} and I_{qr} are the q-axis and d-axis stator and rotor currents, respectively. $\psi_{ds}, \psi_{qs}, \psi_{dr}$ andψ_{qr} are the q-axis and d-axis stator and rotor fluxes, respectively. ω_s is the angular velocity of the synchronously rotating reference frame. ω_r is rotor angular velocity, $R_s$andR_r are the stator and rotor resistances, respectively. The stator and rotor fluxes can be expressed in equations below:

$$\psi_{ds} = L_s I_{ds} + L_m I_{dr} \quad \ldots(9)$$

$$\psi_{qs} = L_s I_{qs} + L_m I_{qr} \quad \ldots(10)$$

$$\psi_{dr} = L_r I_{dr} + L_m I_{ds} \quad \ldots(11)$$

$$\psi_{qr} = L_r I_{qr} + L_m I_{qs} \quad \ldots(12)$$

Where L_s is the self-inductance of stator, L_r is the self-inductance of rotor and L_m is the mutual inductances.

The mechanical and electromagnetic torques are expressed with the following equations [6, 7, 8]:

$$T_m = T_e + J\frac{d\omega}{dt} + f\omega \quad \ldots(13)$$

$$T_e = -P\frac{L_m}{L_s}(\psi_{qs} I_{dr} - \psi_{ds} I_{qr}) \quad \ldots(14)$$

The active and reactive powers (P_s and Q_s) at the stator are defined in equations below:

$$P_S = v_{ds} I_{ds} + v_{qs} I_{qs} \quad \ldots(15)$$

$$Q_S = v_{qs} I_{ds} - v_{ds} I_{qs} \quad \ldots(16)$$

Also the active and reactive powers (P_r and Q_r) at the rotor are defined in equations below:

$$P_r = v_{dr} I_{dr} + v_{qr} I_{qr} \quad \ldots(17)$$

$$Q_r = v_{qr} I_{dr} - v_{dr} I_{qr} \quad \ldots(18)$$

5- WIND FARM STRUCTURE OF SYSTEM MODELED:

The single line diagram of the tested system is shown in Figure (5), modeled in Matlab program (2010b) as shown in Figure (6), The system contains a 9 MW wind farm consisting of six 1.5 MW wind turbines connected to a 33 kV distribution system that exports power to a 132 kV grid through a 30 km, 33 kV feeder.

6- PARTICLE SWARM OPTIMIZATION (PSO)

The Particle Swarm Optimization (PSO) algorithm is a population-based stochastic optimization technique developed by Eberhart and Kennedy in 1995. It is inspired by the natural animal social behavior such as bird flocking and fish schooling. It has been found to be robust in solving continuous nonlinear optimization problems. PSO becomes a focus these days due to its simplicity and ease to implement [9].

A modified PSO was introduced in 1998 to improve the performance of the original PSO. A new parameter called inertia weight is added to the original PSO algorithm [10].

In PSO, each single solution is a "bird" in the search space; this is referred to as a "particle". The swarm is modeled as particles in a multidimensional space, which have positions and velocities. These particles have two essential capabilities: their memory of their own best position and knowledge of the global best. Members of a swarm communicate good positions to each other and adjust their own position and velocity based on good positions [10].

The particles are updated according to the following equations [10, 11, 12]:

$$v(k+1)_{i,j} = w.v(k)_{i,j} + c_1 r_1 \left(g_{best} - x(k)_{i,j}\right) + c_2 r_2 \left(p_{best} - x(k)_{i,j}\right) \quad ...(19)$$

$$x(k+1)_{i,j} = x(k)_{i,j} + v(k+1)_{i,j} \quad ...(20)$$

Where

v_{ij} : Velocity of particle i and dimension j.

$x_{i,j}$: Position of particle i and dimension j.

c_1, c_2 : Known as acceleration constants.

w : Inertia weight factor.

r_1, r_2 : Random numbers between 0 and 1.

P_{best} : Best position of a specific particle.

g_{best} : Best particle of the group.

The PSO tuning algorithm for gains can be illustrated with flow chart as shown in Figure (8).The PSO algorithm is implemented in the following iterative procedure to search for the optimal solution [10,11,12].

1) Initialize a population of particles with random positions and velocities of N dimensions in the problem space.

2) Define a fitness measure function to evaluate the performance of each particle.

3) Compare each particle's present position (xi) with its (xp_{best}) based on the fitness evaluation.

4) If (xp_{best}) is updated, then compare each particle's (xp_{best}) with the swarm best position (xg_{best}) based on the fitness evaluation. If (xp_{best}) is better than (xg_{best}), then set ($xg_{best} = xp_{best}$).

5) At iteration k, a new velocity for each particle is updated by equation (19).

6) For each particle, change its position according to the equation (20).

7) Repeat steps (2)-(6) until a criterion, usually a sufficiently good fitness or a maximum number of iterations is achieved. The final value of (xg_{best}) is regarded as the optimal solution of the problem.

7- SIMULATION RESULTS:

A constant wind speed applied to the modeled system to evaluate its voltage, current, DC-link voltage and generated power. Figure (8-A-B) shows the voltage and current at bus (B400). Figure (9) shows active power in (MW) when using sinusoidal pulse width modulation (SPWM). Figure (10) shows the active power in (MW) when using space vector pulse width modulation (SVPWM). Figure (11) show the generated power in (MW) during SLG fault.

The simulated results of the programmable fault (voltage drop) which applied to Grid of Figure (5), during 0.1 second (5 cycles) at t = 1.23 second shown in Figure (12). The results demonstrates the effect of this fault on active power during it.

After applying variable wind speed to the system, the system not operate as intended at normal operation so to keep the system working in, this situation we need to use an optimization to the control circuits and applying a control system by using PSO to get a new values of gains in PI controllers. These new optimal values of gains make the system operate in the same operation when its input is constant speed.

When the input is variable wind speed and its range of change between (10.5 to 17.5) m/sec. as shown in Figure (13), the system shows a constant voltage response comparing with reducing current to approximately (0.75) p.u from its value as shown in Figures (14, 15, 16). Figure (17) shows the voltages at bus (B400) and Figure (18) shows the currents at bus (B400) which demonstrate the effect of optimization.
Figure (19) shows the active power with variable speed wind after optimization**.**

8- CONCLUSION:

In this work, the modeling of DFIG system is done using the Matlab /Simulink (2010b). The system is also simulated using standard PI controllers. It is concluded that, traditional voltage control technique which is used in both grid-side as well as machine-side converters to analyze the performance of the DFIG system under grid voltage is suitable under sudden change in grid voltage. The main conclusions drawn from this work can be summarized as follows:

1) SVPWM is very practical in control and more efficient in reducing the fluctuations and the rise time of power to reach steady state.

2) The DFIG can operate with variable wind speed and made the optimization to get the normal operation even with variable speed wind by using PSO.

3) Simulation results shows that when the fault occurs the behaviour of the system can be monitored and action is taken

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Table (1) Approximation of power curves [1]

	C_1	C_2	C_3	C4	C_5	C_6	C_7	C_8	C_9
Heier (1989)	0.5	116	0.4	0	_	5	21	0.08	0.035

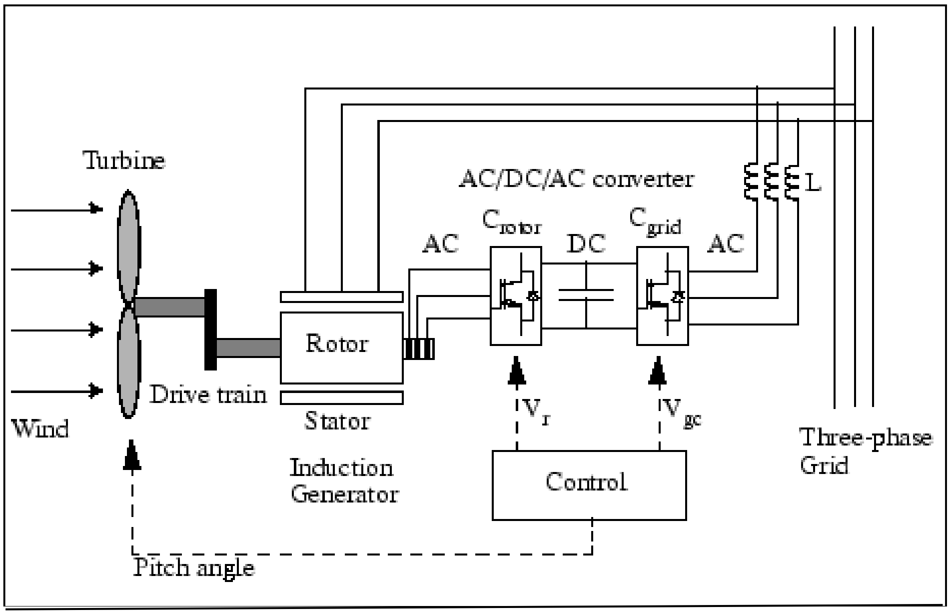


Figure 1: The structure of DFIG controller [2]

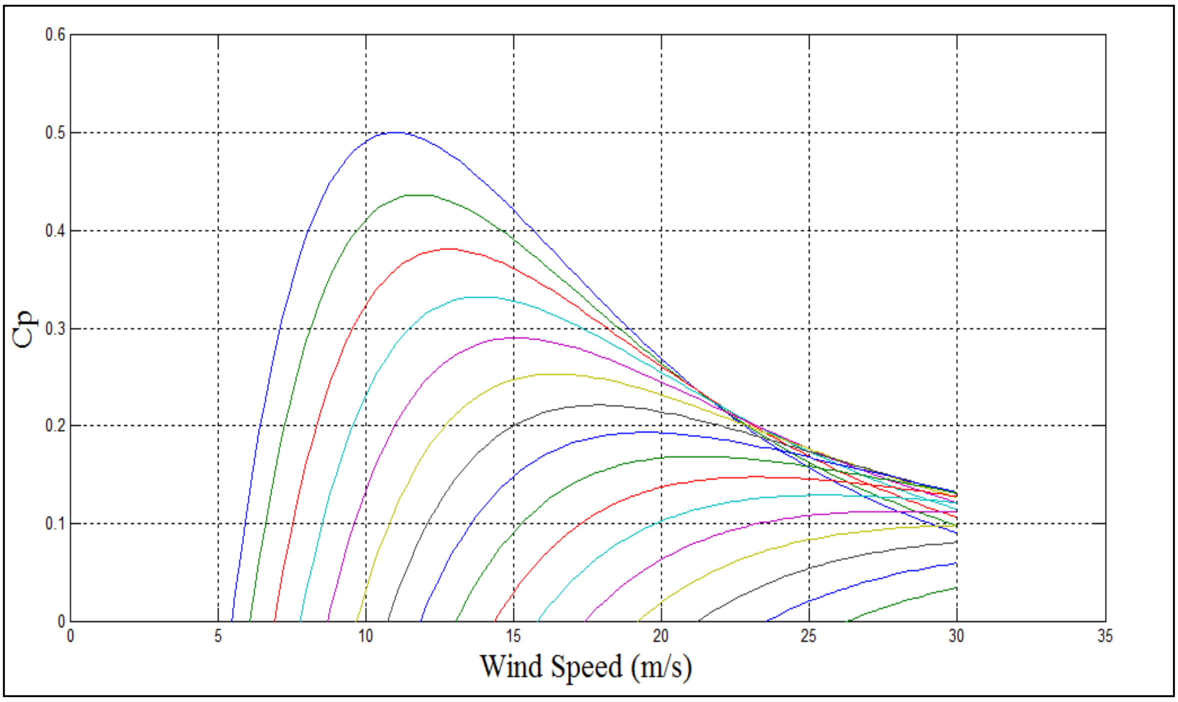


Figure 2: The turbine power coefficient (C_p)

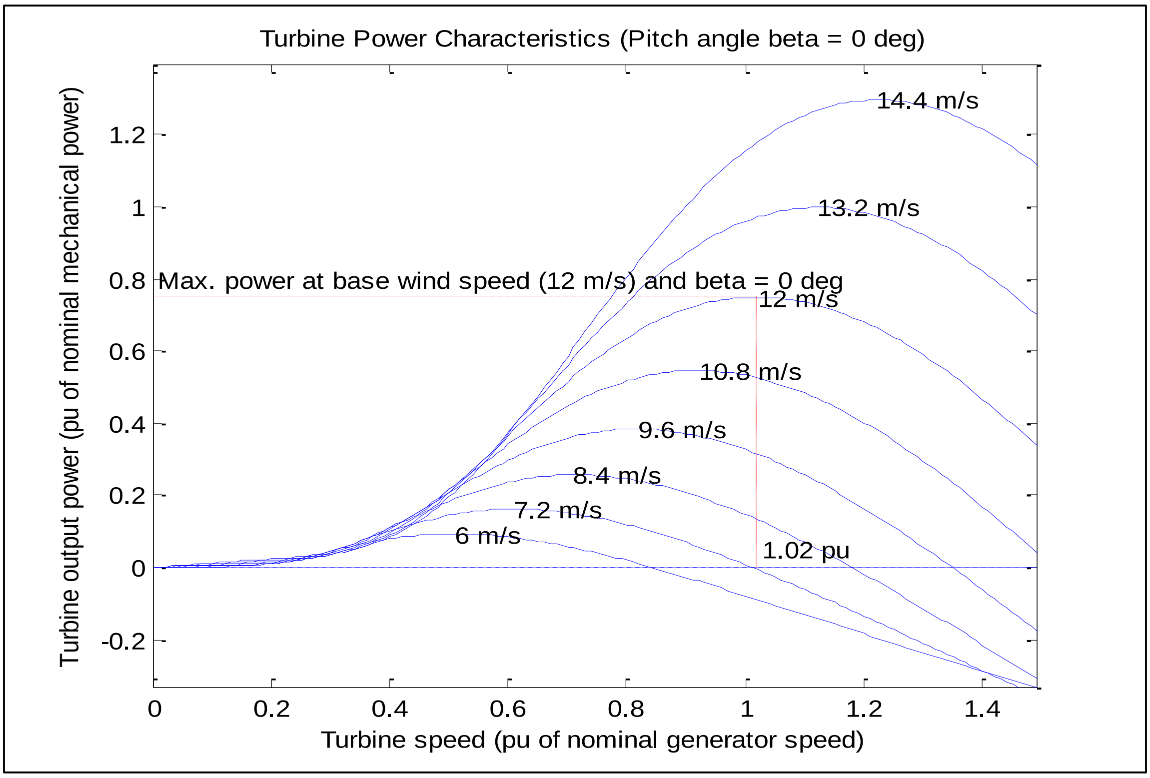
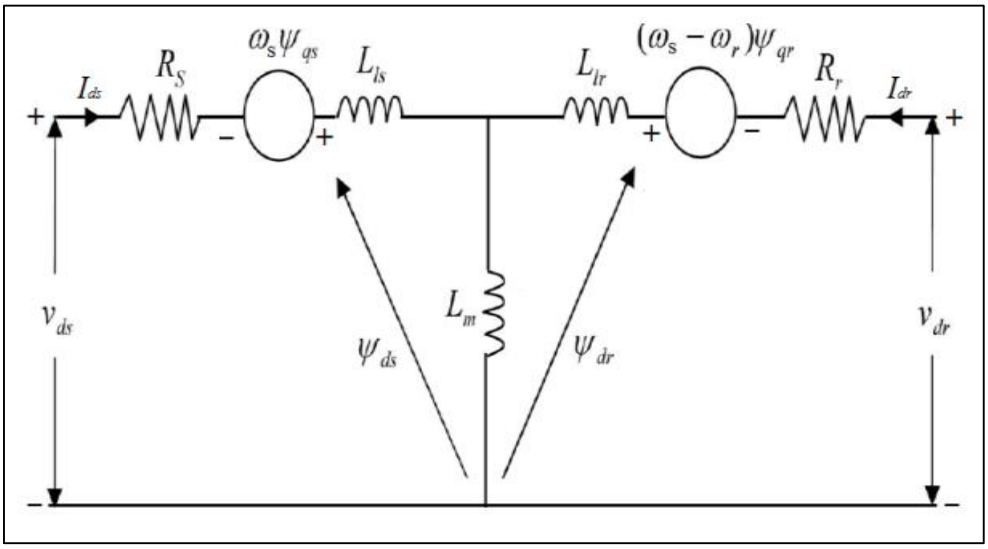


Figure 3: Wind Turbine Power Characteristics for Variable Speed Wind



A- Dynamic d-axis circuit

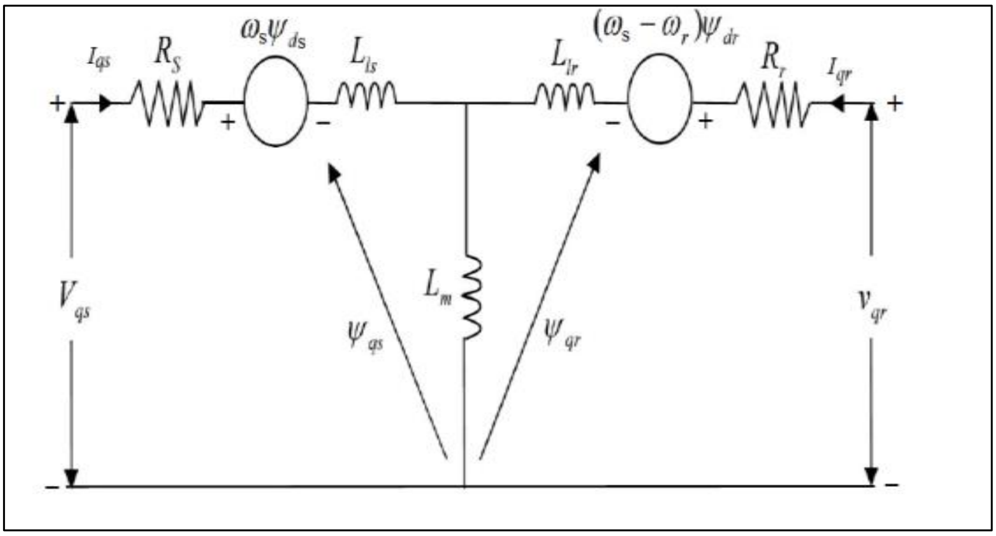


Figure (4): The mathematical model of DFIG

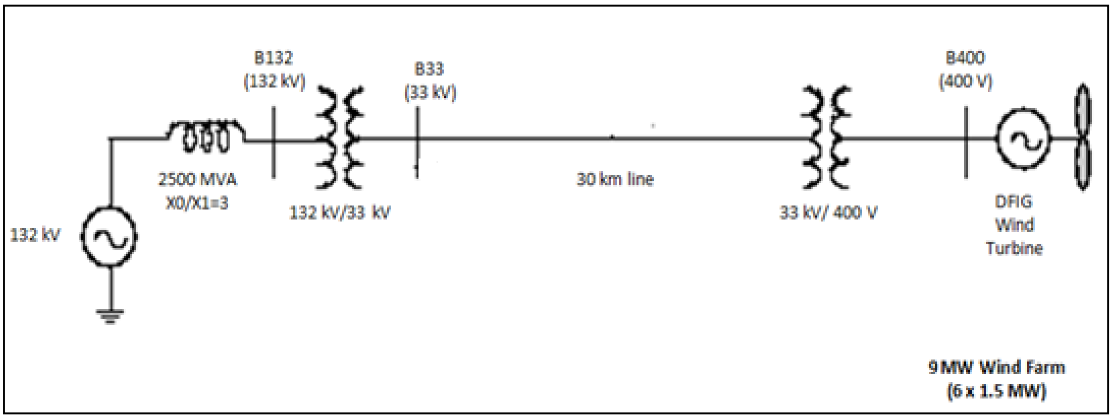


Figure (5): Single-Line Diagram of Wind Farm Connected to the Grid

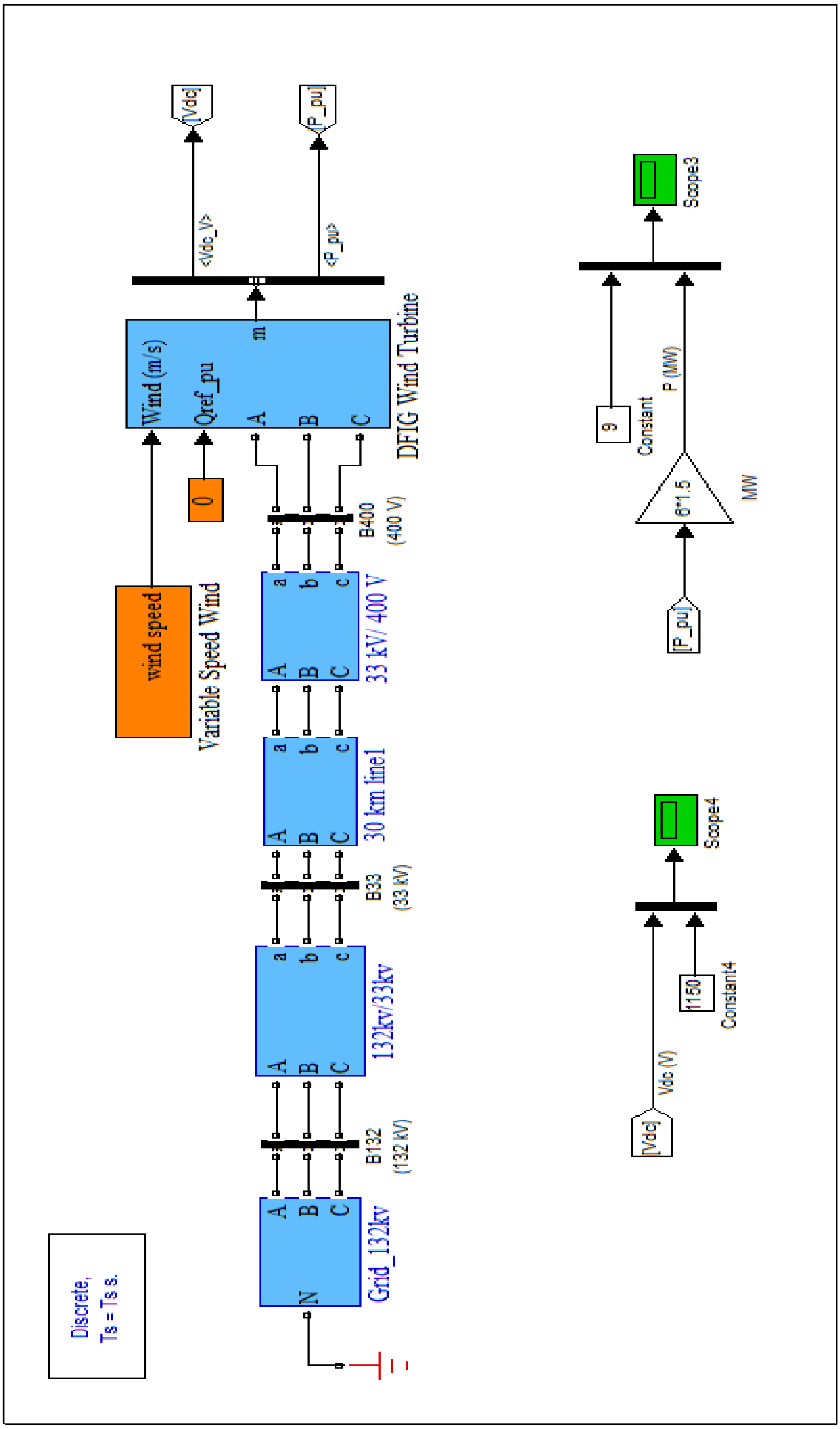


Figure (6): Simulated system model in matlab/Simulink

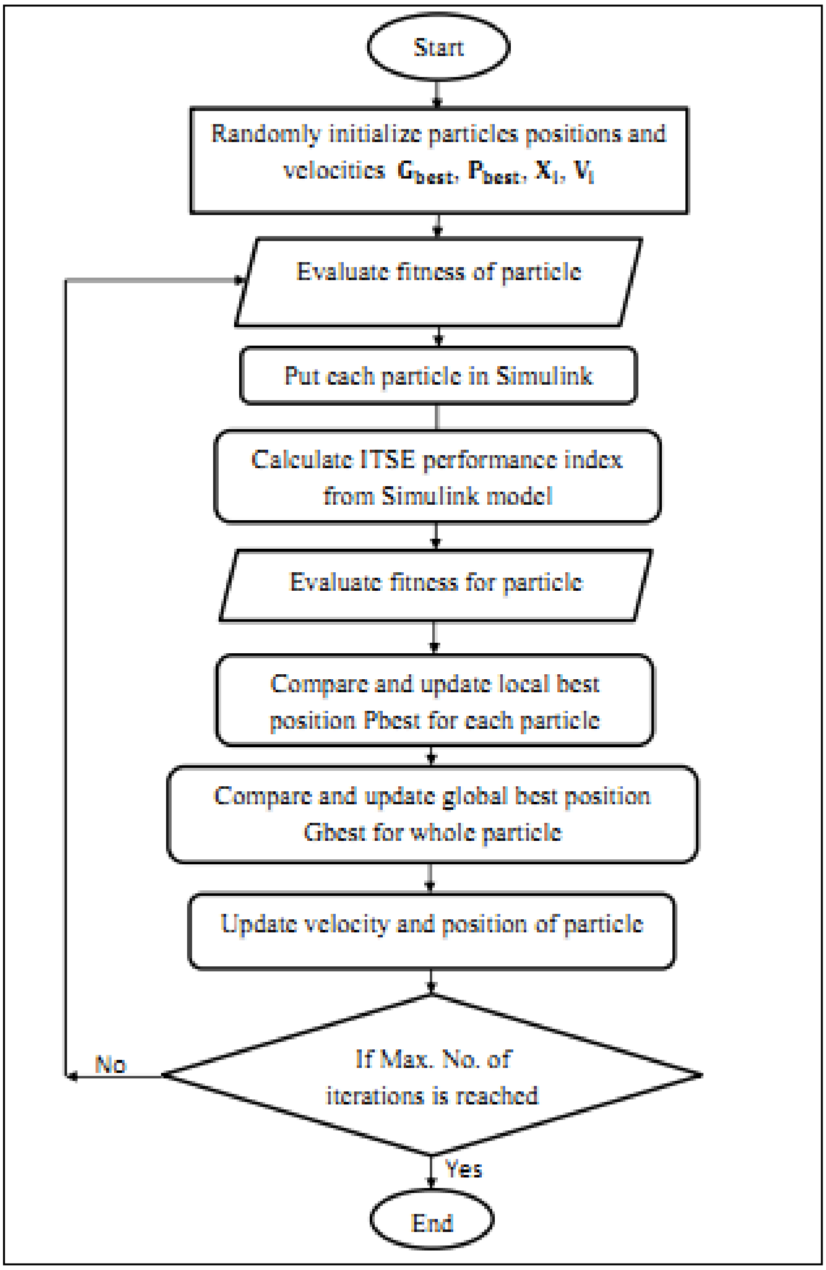
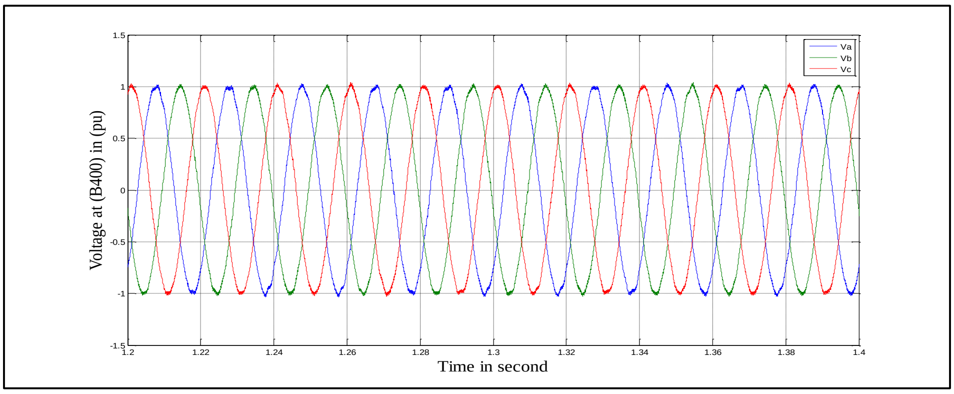
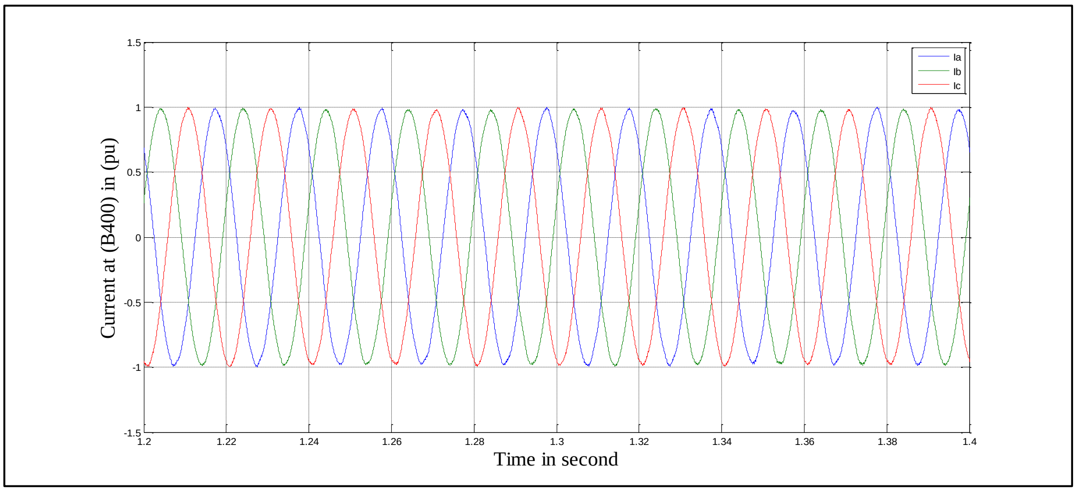


Figure (7): Flow chart of PSO algorithm



A: Voltage at bus (B400)



B: current at bus (B400)

Figure (8): Voltage and Current curves at bus (B400)

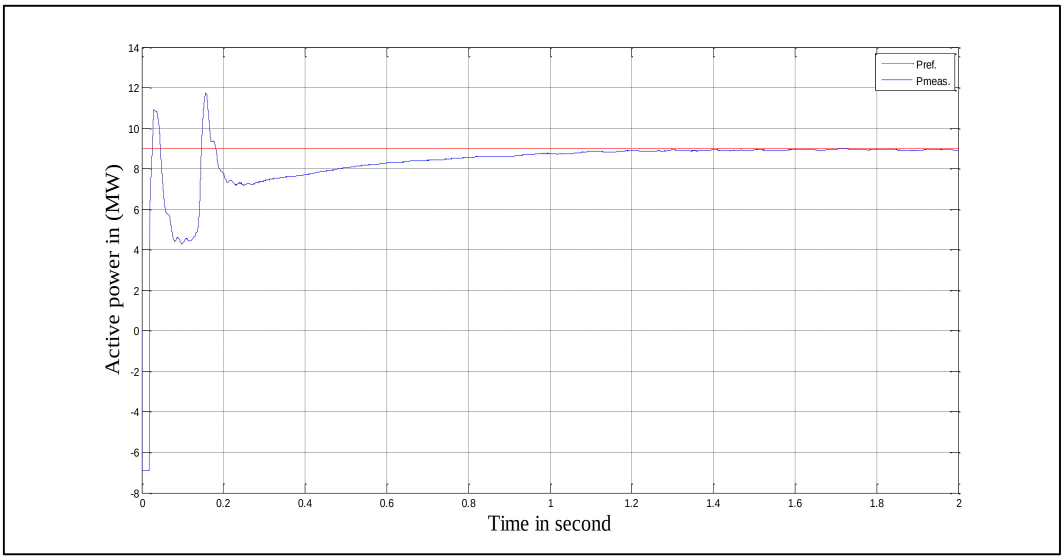


Figure 9: Active power using SPWM

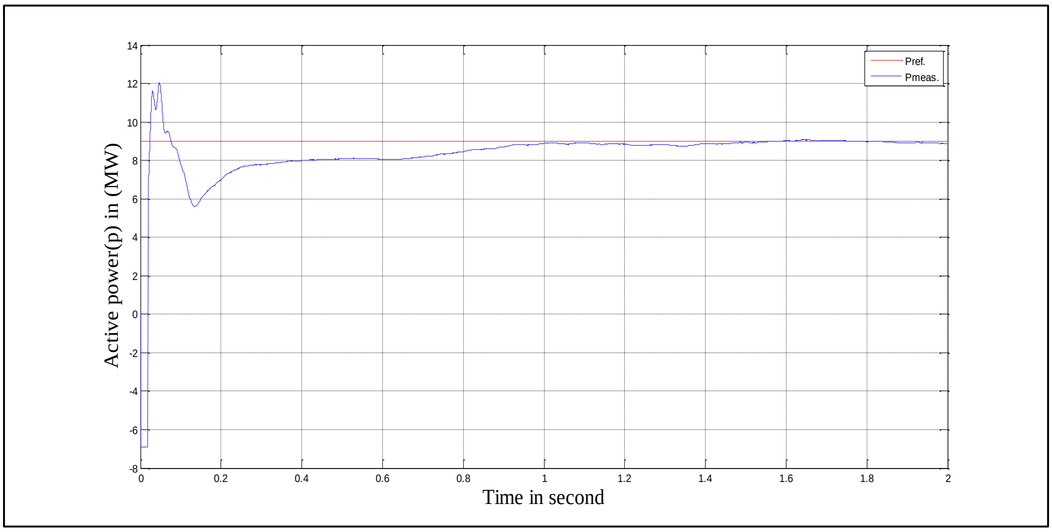


Figure 10: Active power using SVPWM

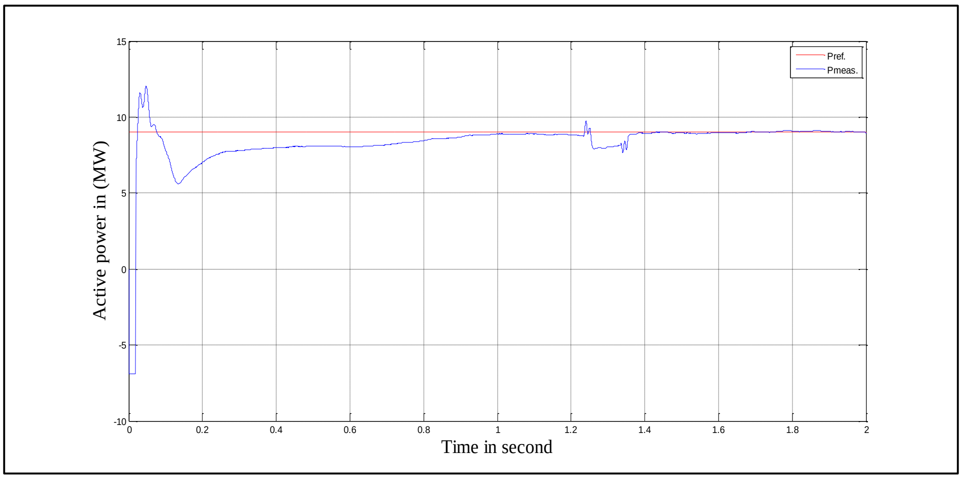


Figure 11: Active power during SLG fault

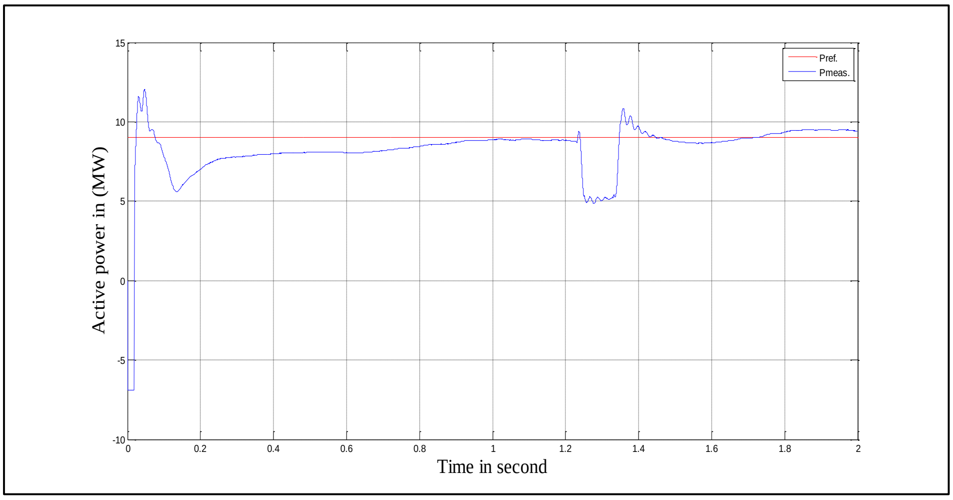


Figure 12: Active power during voltage drop in grid

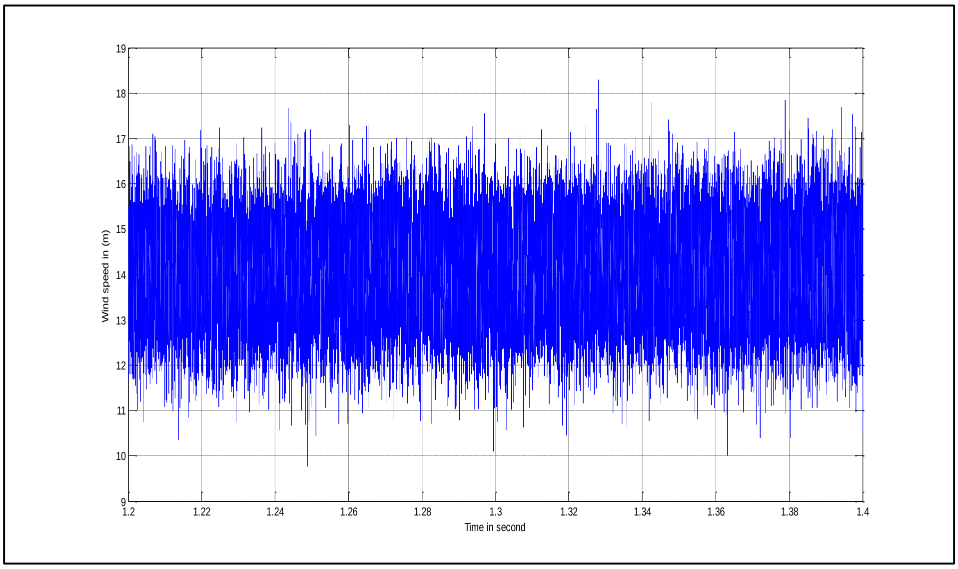


Figure 13: Variable SpeedWind

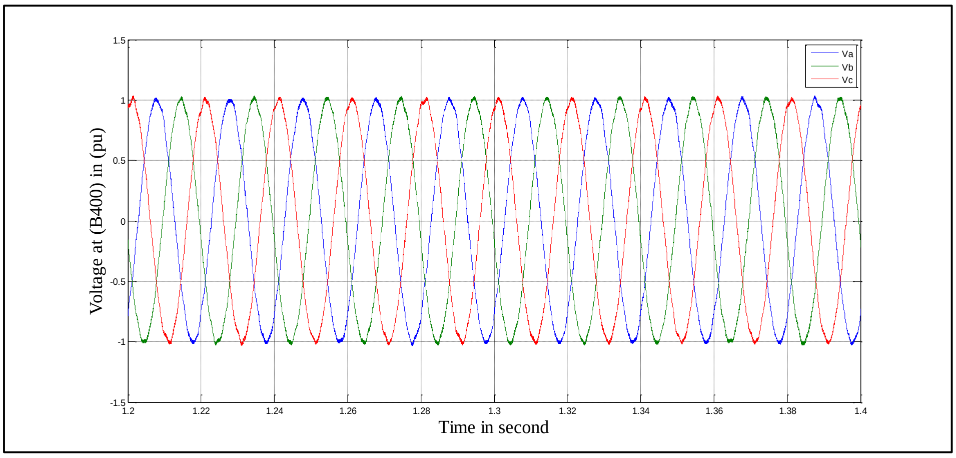


Figure 14: Voltage at bus (B400) with Variable Speed Wind

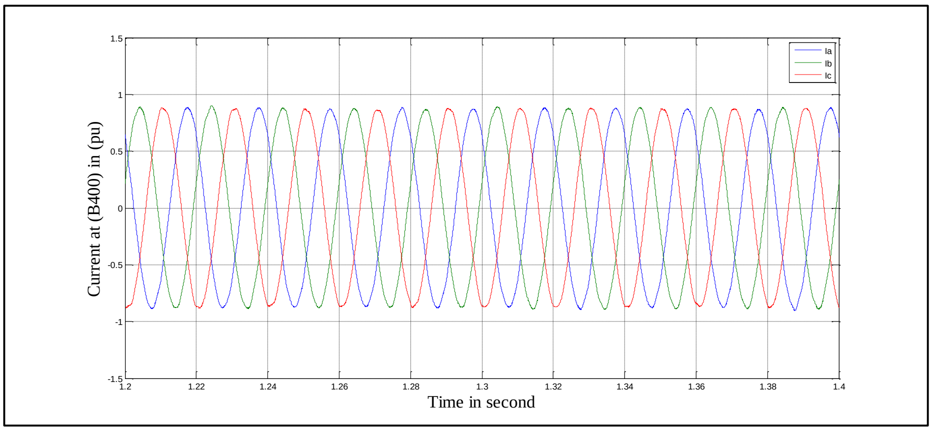


Figure 15: Current at bus (B400) with Variable Speed Wind

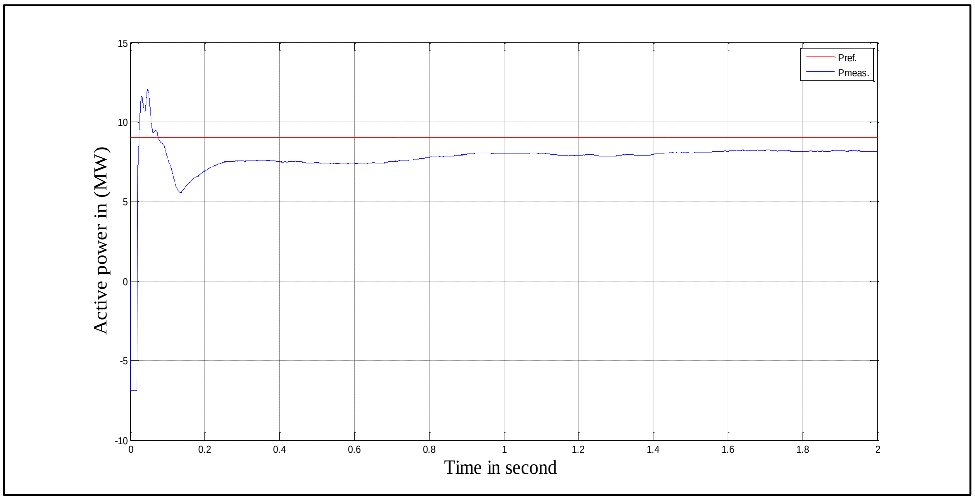


Figure 16: Active power with variable speed wind

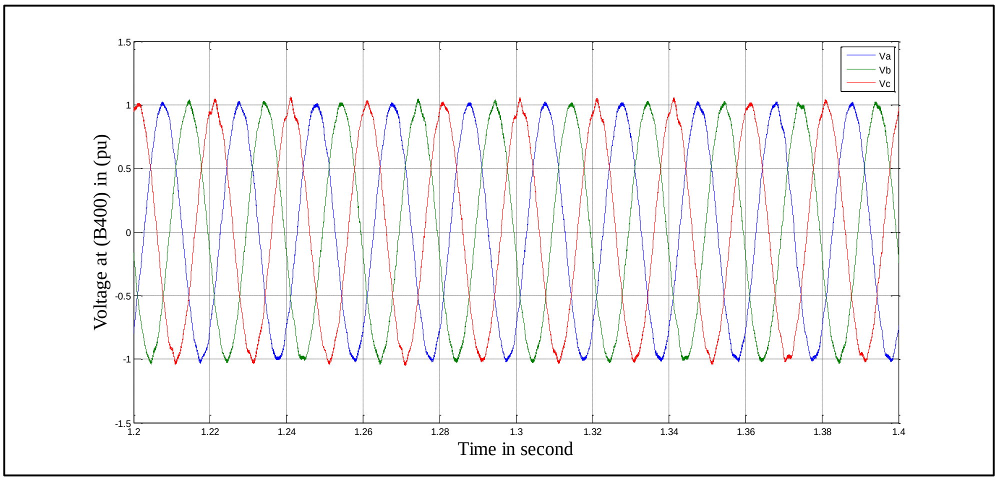


Figure 17: Voltage at bus (B400) with PSO

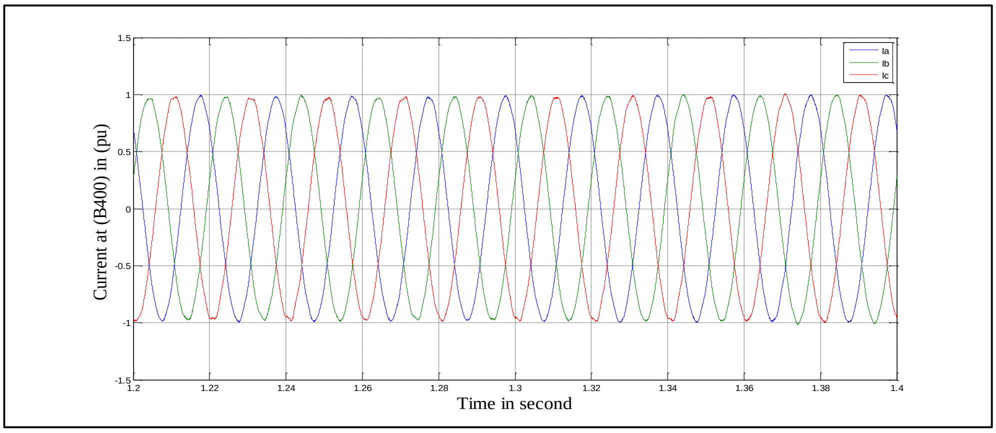


Figure 18: Current at bus (B400) with variable speed wind with PSO

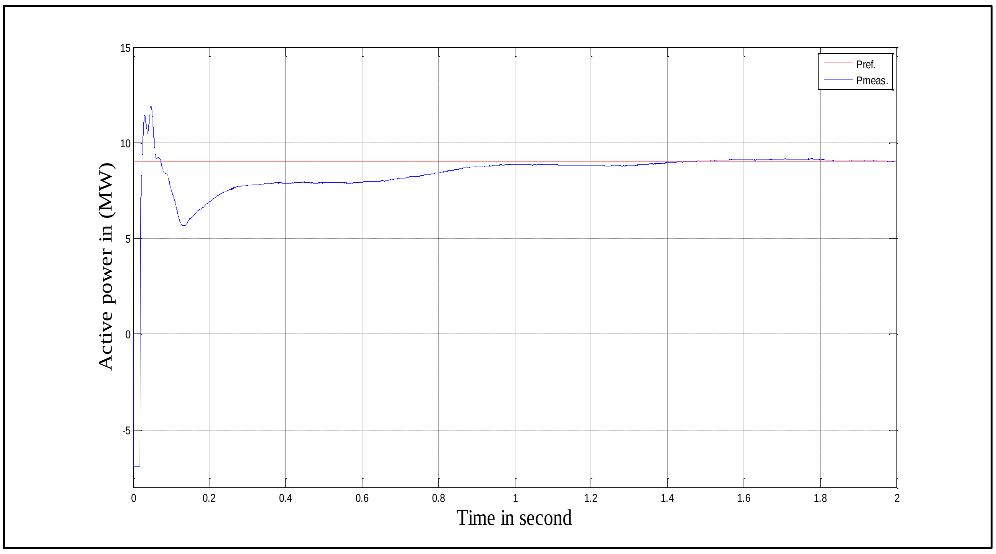


Figure 19: Active Power with PSO

تحسين القدرة الحقيقية للمولد ألحثي الثنائي التغذية مع سرعة الرياح المتغيرة باستخدام امثلية الحشد الجزيئي

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الخلاصة

أصبح نظام تحويل طاقة الرياح (WECS) أكثر شيوعا و جذبا لدراسة امكانية استبدال مصادر القدرة التقليدية بنظام الطاقة المتجددة.

أفضل مثال على ذلك هو المولد ألحثي الثنائي التغذية (DFIG) . وقد أثبتت الإحصائيات أن المولد ألحثي الثنائي التغذية هو أكثر الأنواع نموا في الأسواق التي تعنى بمولدات الطاقة الكهربائية باستخدام الرياح حيث أن له القابلية على العمل بسرعة رياح متغيرة وزوايا اتجاه متغيرة. ويربط عادة مع الشبكة الكهربائية لقابليته على مطابقة جميع متطلبات الشبكة الكهربائية مثل أستقرارية الشبكة, وحدوث الأخطاء ومعالجتها, التزامن مع الشبكة و السيطرة على القدرة. ولكن هذا المولد لا يطابق متطلبات الشبكة الكهربائية بشكل مباشر و أنما يتم ذلك باستخدام دائرة سيطرة لتنظيم عمل المولدة حيث أن الإستراتيجية المتبعة تتم من خلال السيطرة على الجزء الثابت والجزء الدوار للمولد عن طريق دائرة الكترونيات قدرة تتألف من محولين متعاكسين لتطابق متطلبات الشبكة.

يركز هذا المشروع على النمذجة و التحليل للمولد ألحثي الثنائي التغذية (DFIG) باستخدام برنامج الماتلاب لمحاكاة عمل المولد مع سرعة الرياح الثابتة والمتغيرة.

تمت محاكاة ثلاث أنظمة أختبارية باستخدام برنامج الماتلاب MATLAB. أن النظام الأول يعتمد على سرعة الرياح الثابتة باستخدام مضمن السعة النبضية ألجيبي. النظام الثاني فيعتمد على مضمن السعة النبضية للمتجهات المتباعدة. وتم محاكاة كلا النظامين ومعرفة سلوك كل نظام. حيث تم تطبيق نوعين من الاخطاء الأول هو خطأ الخط المفرد عند خط النقل 33 كيلو فولت والثاني هو عند حدوث هبوط مفاجيء في فولتية الشبكة 132 كيلو فولت وهبوطها الى النصف.

النظام الثالث الذي تمت محاكاته أيضا في هذا المشروع هو عندما يكون مصدر الرياح ذو سرعة متغيرة حيث بينت النتائج أن هذا يسبب تقليل في القدرة المتولدة وهنا لابد من معالجة هذه المشكلة لتوضيح إمكانية عمل المولد بسرعة رياح متغيرة وهذا ما تم إثباته من خلال توليف دائرة السيطرة بقيم مثلى لتحقيق هذا المطلب وذلك باستخدام برنامج تحسين وربطه مع برنامج المحاكاة وبرنامج التحسين هو ما يسمى بأمثليه الحشد الجزيئي (particle swarm optimization PSO)