Grid-Connected Bulk Wind Energy System Installing Neural-Controlled Switched Reluctance Generators

Amal Mohamed **Fadia M. A. Ghali** **Khaled S. Sakkoury**
Electronics Research Institute, Cairo, Egypt

Email: amal@eri.sci.eg
Email: fadia@eri.sci.eg

ABSTRACT:

The paper presents modeling and simulation of the wind energy conversion system (WECS) that consists of variable speed wind turbine, switched reluctance generator (SRG), inverter system and neural network (NN) controller. The wind park system under study consists of a number of WECS's operating as utility connected. The input mechanical power fluctuations, induced by operating wind turbines at slightly disturbed wind velocity, lead to inject variable electrical power into the grid. The NN controller is acting on the SRG to assure feeding constant electrical power to the grid at each point of mechanical power fluctuation and each corresponding wind velocity. This objective is achieved by adjusting the on/off switching angles of the SRG power converter. Simulation results are presented to show the main characteristics of the SRG and verification of the proposed WECS control system.

Keywords: Wind Energy Conversion System, Switched Reluctance Machine, Neuro –Controller.

Manuscript received from Dr . Amal Mohamed
Accepted on : 25 / 9 / 2001
Engineering Research Journal Vol 24,No 4, 2001 Minufiya University, Faculty Of Engineering , Shebien El-Kom , Egypt , ISSN 1110-1180

I. INTRODUCTION

The use of efficient medium and large size wind generators for wind energy conversion systems operating as park systems has become a current practice. This fact is emerged due to the ultimate need to exploit all the available sources of renewable energy to meet the growing demand on electrical energy. Therefore, at locations where the metrological data reveals the economic possibility of extracting energy from wind, wind parks are erected either to inject power into local grids or even into unified utilities. Technical specifications and recommendations for each system configuration are well established. Moreover, modern technologies concerning machine design and field construction have helped to a rapid increase in the number of wind power generating facilities worldwide [1,2].

Generally, all generating plants connected to public utilities have to follow specified regulations concerning the voltage/frequency limits and possible injected harmonics. These technical items as subtitles lie under the power quality main topic. In recent years there has been a growing concern about power quality because of the increasing complicity of power systems, diversed types of generation plants and highly demanded services and competition. A variable speed operation of wind turbines is preferred in this case. It has several potential advantages over fixed speed machines; particularly additional energy capture below rated wind speed, additional power train compliance with associated load alleviation above rated wind speed and reduction in audible noise at low wind speed. Several configurations of generator and control system suitable for variable speed wind energy applications have been tested and described in publications. As the switched reluctance machine has preferable characteristics in terms of efficiency, control simplicity and robustness, it has a wide field of application in wind turbines. The machine is also cost competitive with other AC machines. The control aspect of the switched reluctance generator for variable speed wind energy application is discussed in this work [3,4].

Artificial neural networks (ANN) have been used widely as an intelligent control technique in different applications. Many neural control schemes have been proposed, where ANN's can be trained to perform as controller by learning an inverse dynamics of control system from the observation of the input/output relations, or as an emulator by identifying the forward model [5,6]. Previous works have discussed the modeling of the voltage variation and flickers that caused by wind turbines and wind farms resulting in mechanical power fluctuations [7,8].

In this work, the WECS is simulated and the ANN technique is implemented for designing a neuro-controller. This controller is acting upon the SRG to ascertain the injection of fixed electrical power into the grid corresponding to each wind velocity, irrespective from the possible mechanical fluctuations. Simulation results will be discussed using field data.

2. SOURCES OF OPERATION DISTURBANCES:

The schedule problem of wind parks operating in parallel with different types of power plants has been discussed on the basis of operating WECS's at their maximum available power feeding base loads. Whereas gas turbines or pumped storage plants operate to feed maximum demand, or to match rapid changed demand. Therefore, parallel operation of different types of generating plants can give rise to a number of operation problems such as power fluctuations, light flicker, and switching operations.

a) Power fluctuations: Depending on the prevailing wind speeds, the power output from the wind operating facility may change extremely within a short time by practically the full rated power of the turbine. This case takes place if the wind speed changes from one value within the operating rage to another value behind this range. Fluctuating power within the operating range of wind turbines is characterized either by high amplitude with slow rate of rise, or low amplitude periodically recurring fluctuations. The first type of fluctuations are due to high wind speed variations, e.g. between day and night The second type of fluctuations are caused predominantly due to the effects of wind gusting and tower shadow at a frequency at which the rotor blades pass the tower. Hence, the periodic fluctuations are due to fluctuations for high-rated generators installed for wind park operation are reduced as an exponential function of $1/\sqrt{n}$, where n being the number of generators involved [2].

b) Light flicker: Resulting from periodic low amplitude voltage fluctuations, light flicker is one of several well-known power quality problems. It depends on the inherent impedance of the supply system. Therefore, this problem has become a contributing factor in the decision of some wind turbine manufacturers to adopt variable speed wind turbines. This phenomenon can cause disturbances in the network, which leads to consumer annoyance and complaints. As the turbine ratings have increased, flicker has become a more serious problem [3].

c) Switching operations: Different types of machines are equipped with special arrangements to prevent the starting current to exceed 2-3 times the rated power. Despite this limitation, significant system flicker could be observed due to simultaneous start-up of multiple generators and also due to rapid change from full to zero power when the wind turbines have to be braked because of excessive wind strengths.

3. DESCRIPTION OF THE WECS:

The proposed variable speed WECS is presented in the schematic diagram in fig. 1. The wind turbine (WT), is a source of mechanical power. The SRG supplies power across its power converter to the grid through the inverter. The output DC current from the SRG passes through filter in the DC link to smooth the ripples of the direct current. The DC link is connected to the utility busbar through the inverter, whose switches control the proper connection of the WECS to the grid by keeping the variations in frequency and voltage within permissible limits. The NN control unit is connected to the SRG to adjust the θ_{on} and θ_{off} angles, so as to keep the injected electrical power into the grid constant irrespective of the periodic variation in mechanical power.

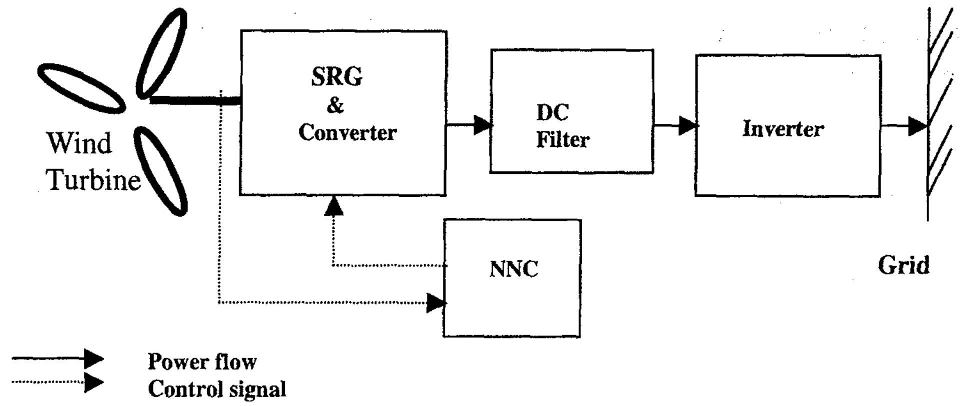

Fig. 1 Block diagram of grid-connected WECS

4. THE SRG CHARACTERISTICS:

The switched reluctance machine does not have rotor winding, while, the number of salient poles on the rotor is different from that on the stator. Since the number of stator and rotor poles are different, the inductance of each phase is a function of the rotor position, and at any instant, the inductance can be different for the three phases. The switched reluctance machine used in this work, the SRG is a 6/4 poles three-phase machine. The cross- section of the SRG is shown in fig. 2. The principle of operation is simple in concept. Since the SRG does not have rotor windings, a source of excitation must be provided. The machine terminals are connected to a capacitor bank to provide a source of excitation. The power converter for one set of three phase stator windings is shown in fig. 3. The power switches provide a path to supply the winding current as the rotor pole nears alignment with the stator poles. This is just to provide the magnetizing current. Diodes provide a path for current to flow out of machine as the rotor poles are driven past alignment when its inductance is in the negative slope region as shown in fig. 4. Since there is a reluctance torque attempting to keep the stator and rotor poles aligned, work must be done by the prime mover to force the poles apart, which appears as an for this machine are given as follows:

$$V = Ri + L(\theta)\frac{di}{dt} + i\frac{dL(\theta)}{dt}\omega \qquad (1)$$

$$\frac{d\omega_r}{dt} = \frac{1}{J}(T_m - T_e) \qquad (2)$$

$$T_m = P_m / \omega_r \qquad (3)$$

$$T_e = \tfrac{1}{2} i^2 \frac{dL}{d\theta} \qquad (4)$$

Where: V is the supply voltage, i, R, L, are the phase current, resistance and inductance, θ, ω_r are the rotor position and speed, T_m, T_e are the input mechanical torque and the required electrical torque respectively.

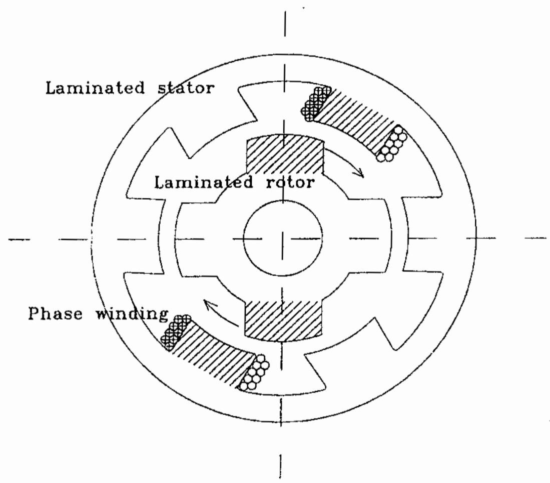

Fig. 2 A cross-sectional view of 6/4 poles Switched Reluctance Machine.

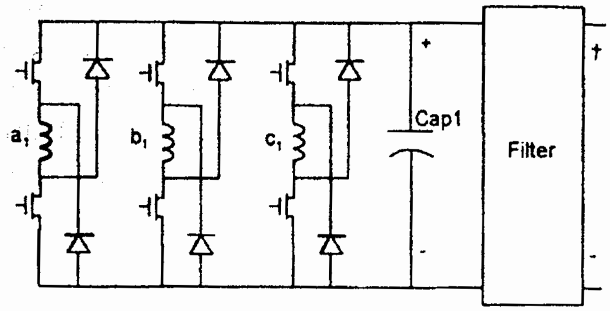

Fig. 3 The schematic diagram of the three-phase converter of the SRG.

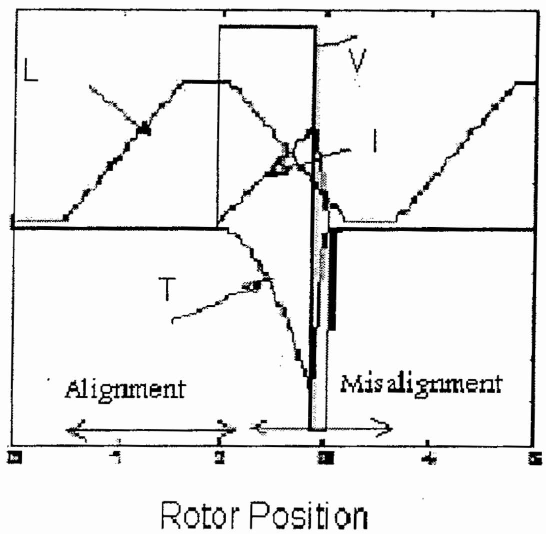

Fig. 4 variation of L,I,T, and V versus rotor position.

5. THE CONTROL SYSTEM DESIGN:

Since the SRG delivers DC voltage and the WECS is connected to AC grid, an intermediate inverter stage is required. Moreover, the inverter stage should meet the grid-connection requirements considering the voltage/frequency levels and permissible violations irrespective of any source of fluctuations. This objective is realized by controlling the switching angles of the inverter independent of the

the SRG, is acting upon the switching angles of the converter to assure constant electrical power for each wind velocity irrespective of the fluctuating mechanical power. Therefore, the mechanical power obtained from the wind turbine is given by the following equation:

$$P_m = P_{mo} + \Delta P_m \sin \omega t \qquad (5)$$

Where: P_{mo} is the mean value, ΔP_m the amplitude of mechanical power oscillations and $\omega_1 = 2\pi f_1$ the angular speed of the mechanical power oscillations,

$$P_{mo} = \tfrac{1}{2}\rho\pi R^5 \frac{c_p}{\lambda^3}\omega_r^3 \qquad (6)$$

Where: c_p is the power coefficient, $\lambda = \omega_r R/V_w$ is the tip speed ratio, R is the rotor blade radius of the wind turbine, ρ is the air density and V_w is the wind velocity.

The generated output power from the SRG is given by:

$$P_{out} = NV_{dc} I_{dc} \qquad (7)$$

Where: N is number of phases and V_{dc}, I_{dc} are the phase DC voltage and current respectively.

5.1 THE NEURO-CONTROLLER DESIGN:

The neuro controller is used to learn the current profile (θ_{on} , θ_{off}) for a particular rotational speed in order to obtain the desired output power. In this application a multi- layer feed forward neural network based on backpropagation learning technique is chosen for its simplicity [10]. The network structure has three layers, the input layer, the output layer, and one hidden layer. The number of neurons in the input layer, in the hidden layer and the output layer are 2, 3, and 2 respectively. The input to this controller are the mechanical power and the rotational speed, the outputs are the turn on and the turn off angles of the SRG converter. The block diagram describing the controlled SRG is shown in fig. 5. The neuro-controller is trained off-line for the operating pattern of the wind turbine (P_m, ω_r) and the desired pattern of (θ_{on} , θ_{off}). The performance of the neuro-controller is illustrated in the simulation results in the following section.

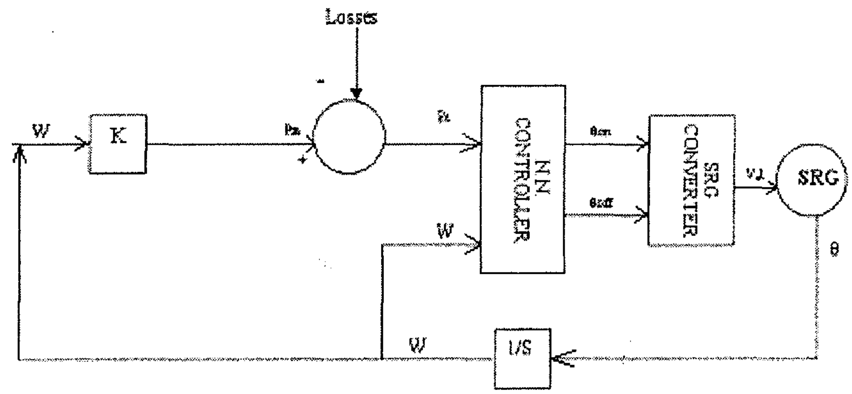

Fig. 5 Block diagram of NN controlled SRG.

6. SIMULATION RESULTS:

To illustrate the SRG special performance and the control strategy employed for the WECS to overcome the problem of fluctuated mechanical power a SRG machine with nominal values of 60 kW and terminal voltage of 240 V per phase is used to carry out the simulation. Figure 6 shows the phase current of the SRG with the idealized inductance profile and supply voltage at 1850 rpm. It is shown that at turn on angle (θ_{on}) the current is building up slowly for the purpose of excitation of the SRG.
At the turn off angle (θ_{off}) the switches of the power converter are switched off and the supply voltage becomes negative. In the reverse period, from θ_{off} - θ_q the current rises faster and this bulk current flows out through the diode of the converter. Figure 7 shows the instantaneous output power from SRG per phase over one electrical cycle. The positive part of the power curve indicates the excitation powers delivered to the machine from the DC supply while the transistors are conducting during the conduction period (θ_{on} - θ_{off}).

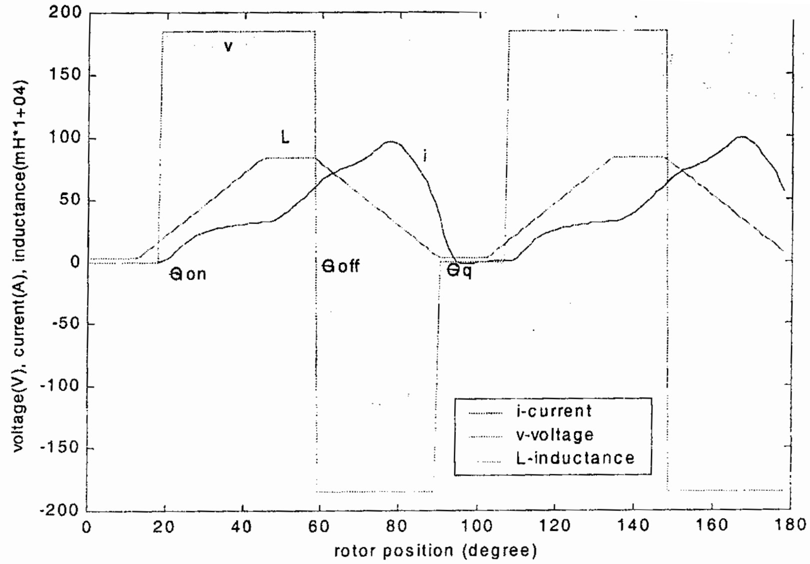

Fig. 6 The phase current of the SRG.

The negative part represents the output power during the de-fluxing period (θ_{off} - θ_q). It is clear that the returned output energy is exceeding the excitation energy to keep the generation action and the difference in this electrical input power and electrical output power is provided by the prime mover (input mechanical power).

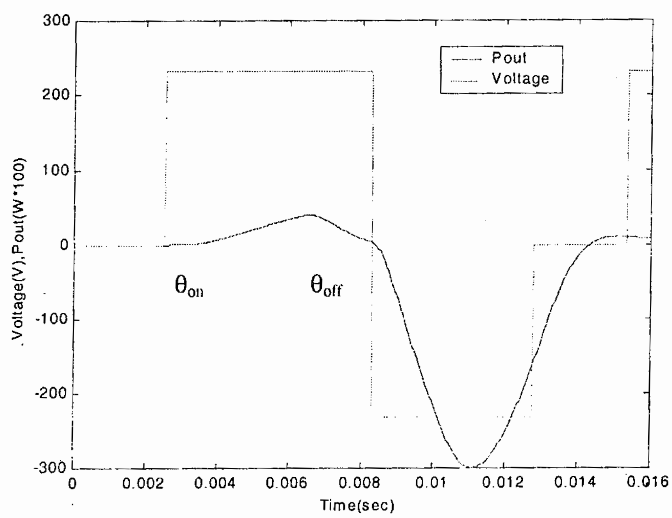

Fig. 7 The output power of the SRG.

In fig. 8 the output mechanical power has two levels, one with a nominal power P_{mo} of 1 pu corresponding to V_w of 10 meter/sec and the other one has a P_{mo} of 0.8 pu when the V_w changed to 9 m/sec. Super-imposed on each power level is the output power fluctuation of the wind turbine with 1Hz oscillating frequency. Therefore, two cases will be studied for the control system according to fig. 8.

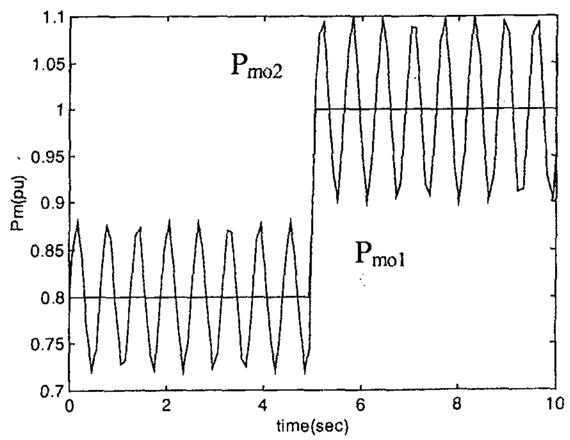

Fig. 8 The mechanical power fluctuation at two levels of P_{m0}

Tables1, and 2 indicate the output characteristics of the WECS with the control system. They show that the increase or decrease of the input mechanical power will be met with changing of the input electrical power by controlling the switching angles of the SRG. There is a set of pairs of turn on and turn off angles (θ_{on} - θ_{off}) , which will provide the same specified output power at a particular speed. So the resultant output power is constant. In this analysis we neglect the calculation of losses.

Case (1):

It represents the mechanical power fluctuation with P_{mo1}=40 kW , $P_{mo1}+\Delta P$=45, and $P_{mo1}-\Delta P$=35 at rotational speed of 1650 rpm. The excitation power P_{ex} compensates for the differences of the input mechanical power by changing the switching angles of the SRG

converter. The augmented ...
excitation power P_{ex} are almost equal to the actual output power, P_{out}.

Table 1 Constant P_{out} with fluctuated P_{mo1}

ω_r (rpm)	**Pm** (kW)	**Pex** (kW)	**Pout** (kW)
1650	40	17.7	57.3
1650	45	12.8	57.4
1650	35	22.6	57.1

Case (2):

The mechanical power P_m changed from P_{mo1} to P_{mo2} due to the variation of the rotational speed from 1650 to 1850. Table 2 indicates the increase and decrease of the electrical excitation by changing the excitation angles (θ_{on} - θ_{off}).

Table 2 Constant P_{out} with variation of P_m.

ω_r (rpm)	**Pm** (kW)	**Pex** (kW)	**Pout** (kW)
1650	40	17.7	57.3
1850	50	7.9	57.6

7. CONCLUSION:

In this work, we investigated the main features of using the switched reluctance machine as generating units of WECS. We discussed the problem of the input mechanical power fluctuations, induced by operating wind turbines at slightly disturbed wind velocity, which lead to inject variable electrical power into the grid.

The main characteristics of the SRG and its simple control system showed how to overcome of this problem. A NN control strategy is used for its high performance to act on the SRG to assure feeding constant electrical power to the grid at different mechanical power fluctuations and each corresponding wind velocity. This function is achieved by adjusting the on/off switching angles of the SRG power converter. Simulation results are presented for verification of the proposed WECS control system. A future work will be continue to study the inverter stage which connect the DC link from the SRG to the AC link into the grid of the WECS proposed in this work.

7. REFERENCES:

[1] Manfred Fischdeck, Martin Kaltschmitt, "Integration Einer Windtechnischen Stromerzeugung In Den Konventionellen Kraftwerkspark", European Community Wind Energy Conference, Germany, 8-12 March, 1993, pp. 778-781.

[2] Hans-J. Fiss, Karl-Heinz-Weck, "Connection of Wind Power Generating Facilities to the Power Distribution System and Potential Effects on the System", European Community Wind Energy Conference, Germany, 8-12 March, 1993, pp. 747-750.

[3] R. Cardenas, W. Ray, and G. Asher: "Transputer Based Control of A Switched Reluctance Generator for Wind Energy Applications." Proc. Of EPE Conf., Espain, 1995.

[4] R. Cardenas, W. Ray, and G. Asher: " Switched Reluctance Generators for wind Energy Applications." IEEE Power electronics specialist Conf., Atlanta-Gorgia, June 1995.

[5] B. Kosko, : "Neural Netowrk and Fuzzy System, A Dynamical Approach to Machine Intelligence." Englewood Cliffs, N.J. Prentice Hall,1990.

[6] F. Ismail, S. Wahsh, and A.Mohamed, "Fuzzy-Neuro Based Optimal Control of Variable Reluctance Motor," Proc. of the IEEE International Conf. on Control Application, Albany, New York, U.S.A, Sept. 28-29, 1995.

[7] Z.S. Saoud, and N. Jenkins: ...
Induced by large wind turbines." IEEE Trans. on Energy Conversion, Vol. 14, No 3, Sept. 1999.

[8] A. Feijoo, and J. Cidras: " Analysis of Mechanical Power Fluctuations in A synchronous WEC's." IEEE Trans. on Energy Conversion, Vol. 14, No 3, Sept. 1999.

[9] T.J.E. Miller, "Switched Reluctance Motors and Their Control." Oxford university press, 1993.

[10] D. Reay, T. Green, and B. Williams, "Neural Networks Used for Torque Ripple Minimization from a Switched Reluctance Motor." Proc. of the European power electronics conference, EPE'93, Brighton, Sep, 1993.

ربط الشبكات الكهربية بنظام طاقة الرياح باستخدام موالدات الممانعة المتغيرة ذات التحكم بالشبكات العصبية

امال زكى محمد فادية أمين غالى خالد سيف سكورى
معهد بحوث الالكترونيات
القاهرة – جمهورية مصر العربية

ملخص البحث:

يقدم هذا البحث نمذجة و محاكاة نظم تحويل طاقة الرياح الى طاقة كهربية و الذى يتكون من توربينة هوائية متعددة السرعات، المولد ذو الممانعة المتغيرة، محول عكسى و محكم يعمل بتكنولوجيا الخلايا العصبية و هذا النظام الكامل يشتمل على عدد من هذه الوحدات و التى يتم ربطها جميعا على الشبكة الكهربية. و عند نقل الطاقة الميكانيكية من التوربينة الهوائية توجد مشكلة التغير فى الطاقة نتيجة التغير الطفيف فى سرعات الرياح و تؤدى هذه التغيرات فى الطاقة الميكانيكية الى تغيير فى الطاقة الكهربية الناتجه من المولد الكهربى و التى تنتقل الى الشبكة الكهربية و للتغلب على هذه المشكلة تم استخدام تكنولوجيا الشبكات العصبية لتصميم محكم يقوم بالتحكم فى المولد ذو الممانعة المتغيرة و ذلك بتغيير لحظات فتح و غلق مفاتيح محول الطاقة للتحكم فى الطاقة الناتجه من المولد. و تقدم النتائج خصائص المولد ذو الممانعة المتغيرة والتحقق من فاعليه نظام التحكم.