A WIND TURBINE SIMULATOR USING ANN CONTROLLED DC DRIVE

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Abstract This paper presents a new simulator using a dc motor drive to simulate the characteristics of a vertical-axis wind turbine in steady-state operation. The drive system consists of a separately excited dc motor fed via a thyristor converter. This drive is controlled by its Artificial Neural Network (ANN) inverse model using the wind turbine model as a reference. The controller is implemented by a LabView software program which provides a great flexibility and gives the possibility to simulate any wind turbine characteristics. The proposed simulator is tested for both dynamic and steady state modes at different wind velocities and loads. It is shown that the steady-state characteristics of the proposed simulator follow, satisfactorily, those of the actual wind turbine.

List of symbols

A = area of the wind turbine blade, m^2,
$C(\lambda)$ = coefficient of the wind turbine performance,
I_a = average armature current, A,
K = machine constant, N-m/A.Wb,
n = mechanical speed of the turbine (motor), rpm,
$n(k)$ = the motor speed at the instant k, rpm,
$n_v(k)$ = tacho-generator output at the instant k, V,
r_m = maximum radius of the rotating turbine, m,
R_a = armature resistance, Ω,
T_m = average developed torque, N-m,
U = wind velocity, m/s,
U_{ref} = wind velocity reference, V,
V_a = applied armature voltage, V,
ϕ = magnetic flux per pole, Wb,
ρ = air density, Kg/m^3,
λ = tip speed ratio,
ω = $2\pi n/60$, mechanical speed of the turbine (motor), rad/s.

1. Introduction

Recently, the interest in wind energy has been increased, where it is considered one of the most important and promising forms of renewable energy sources[1]. The wind energy conversion systems (WECS) have been increased around the world either as part of public grid or as isolated power generating units. For instance, in France, a project (EOLE2005) aims at increasing the installed wind energy capacity to several hundreds of MW by the year 2005[2].

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The rapid progress which has been achieved in the development of variable and economic WECS has made it possible to gain experience in designing, manufacturing and testing different types of WECS[3]. To achieve those

experimental tests, models for the wind turbine have to be built. On the other hand, the test procedures have to wait for a natural wind with appropriate velocity or use an artificial wind which may need a long time and high cost. To avoid these problems, a wind turbine simulator is necessary to design and test different types of WECS[4,5]. Several wind turbine simulators have been developed, but their performance and flexibility need to be improved[3-5]. A manual control of the armature and/or field voltage of the dc motor has been introduced to simulate the vertical axis wind turbine[4], but the armature circuit resistance needs to be continuously changed to change the operating point on the torque-speed characteristics. Another method for wind turbine simulation based on wind turbine characteristics has been presented[3], but it is expensive and relatively complex. It uses a micro-controller connected to the serial port of a personal computer and communicates with it through a transmitter. An alternative method based on control of the armature voltage of a separately excited dc motor, such that the motor tracks the wind turbine characteristics has also been reported[5]. However, that method was implemented using operational amplifier circuits whose parameters were adjusted for a certain operating point of a piece-wise linear model of the non-linear system. Those circuits have the tendency to drift with age and temperature causing degradation of the system performance.

In this paper, a new simulator for simulating a vertical axis wind turbine in various modes of operation using a separately excited dc motor fed from a thyristor converter is proposed. The proposed simulator is controlled by an ANN inverse model of dc motor drive (converter/motor/load) using the wind turbine model as a reference. The ANN's role is to model the non-linearties and parameter uncertainties of the motor drive[8-10]. This model allows mapping at high precision with the wind turbine reference model. This controller is implemented using a personal computer with LabView software through a data acquisition card Lab-pc1200. The proposed simulator is tested for both dynamic and steady state modes at different wind velocities and loads for 17m Darrieus turbine. This simulator is also tested to simulate other wind turbines by modifying parameters of the wind turbine reference model

2. Vertical Axis Wind Turbine

There are two basic types of wind turbines that are commonly used in different regions of the world[4-7], i.e of horizontal axis or of vertical axis. The present work considers a vertical axis wind turbine such as that shown in Fig. (1). It has several attractive features[6,7]. For instance, the turbine rotates about a vertical axis, and hence it does not need to be oriented into the wind. Also, the blades take the shape of a jumping rope experiencing high centrifugal force. The blades operate in almost pure tension, and so a relatively light and inexpensive blades are sufficient. In addition, the power train, generator and controls are all located near ground level. Hence they are easy to construct and maintain. The efficiency of this type is nearly as good as that of the horizontal axis propeller turbine. So, the vertical axis wind turbine holds considerable promise as a cost-effective turbine.

The average output torque T_T of the wind turbine is given by[3-7]:

$$T_T = 05 \rho r_m A C(\lambda) U^2 \qquad (1)$$

The coefficient of performance C(λ) is a non-linear function of the tip speed ratio:

$$\lambda = \frac{\omega r_m}{U} \qquad (2)$$

The variation of C with λ for one of those turbines called Darrieus wind turbine is shown in Fig.(2). The torque-speed characteristics of such turbine, based on eqns. (1) and (2), are shown in Fig.(3)[4,7].

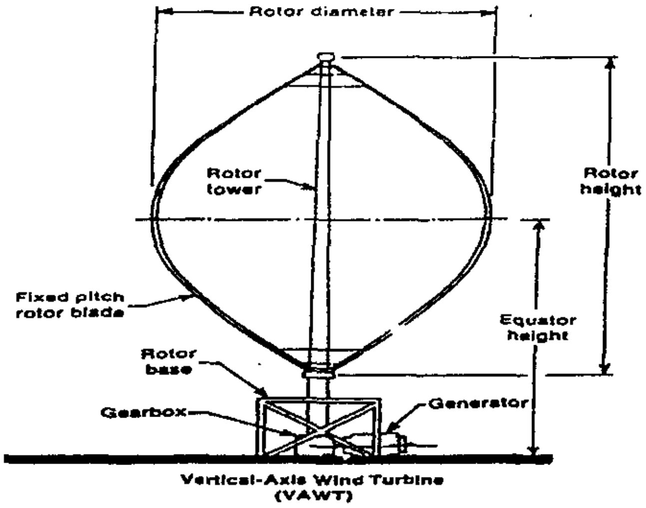


Fig. 1: Vertical-axis wind turbine.

3. Control Algorithm

The objective of the control algorithm is to design a controller for the dc drive such that the torque-speed characteristics of the real wind turbine can be tracked. The dc motor can be represented by the following two steady state equations[4,5]:

$$\begin{aligned} T_m &= K\phi I_a \\ V_a &= K \phi \omega + R_a I_a \end{aligned} \qquad (3)$$

If the dc motor is separately excited, the flux ϕ becomes a constant, and from eqn.(3), it is seen that the torque is directly proportional to the armature current I_a. Since it is desired to simulate the output torque-speed characteristics of the wind turbine by that of the dc motor, eqns (1) and (3) give:

$$I_{ref} = K_T \, C\,(\lambda)\, U^2 \qquad (4)$$

By controlling the applied armature voltage V_a, the armature current I_a can be forced to track the reference current I_{ref}, given by eqn.(4). From C(λ) given by Fig.(2) and eqn.(2), I_{ref} is a function of the motor speed n with the wind velocity U as a parameter. So, it is possible to simulate the torque-speed characteristics of the vertical axis wind turbine such as shown in Fig.(3)[4,7].

4. The Proposed Wind Turbine Simulator

The characteristics of the vertical axis wind turbine is simulated using a separately excited dc motor supplied by a single phase half-controlled bridge. The system components are shown in Fig. (4). The "PC controller" of Fig. (4) is as shown in Fig.(5). The dc motor is loaded using an electric brake, and so the brake arm is used to impose different loading conditions to the simulator. The components T_1, T_2, and T_3 are dedicated to the measurements and signal conditioning.

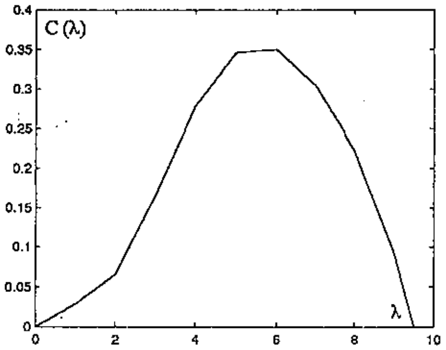


Fig. 2: C(λ)versus tip-speed ratio λ for 17m Darrieus turbine.

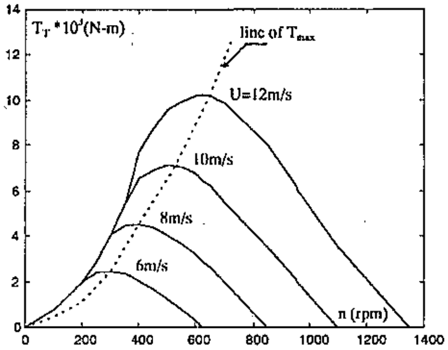


Fig.3: Torque-speed curves of 17m Darrieus at different U.

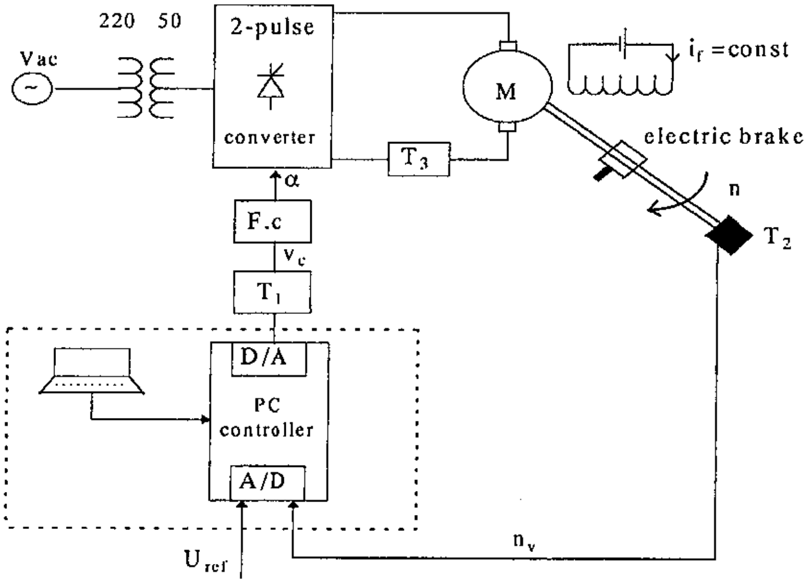


Fig.4: Schematic diagram of the proposed wind turbine simulator.

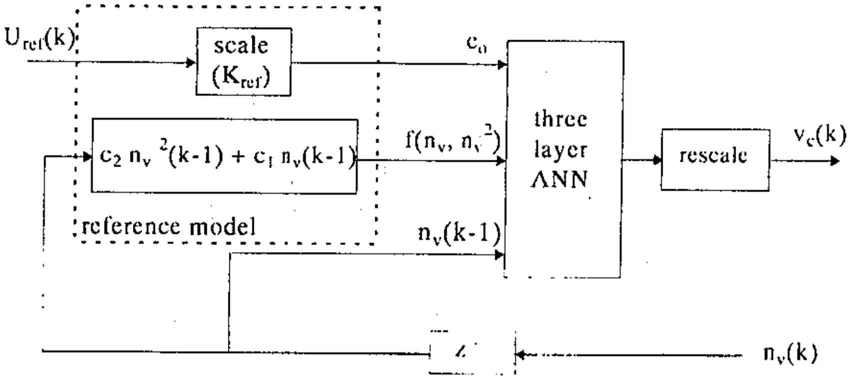


Fig 5: The controller block diagram for the proposed simulator.

As shown in Fig.(5), the controller uses ANN inverse model of the dc motor drive in conjunction with the wind turbine model as a reference. The ANN inverse model is used as feedforward rules to calculate the appropriate control signal for the converter in order to manipulate its terminal voltage in such a manner as to make the motor torque-speed characteristics follow that of the wind turbine.

4-1. Wind turbine reference model

The first step for the controller design is to select a suitable reference model for the motor current I_a to follow the wind turbine trajectory, I_{ref}, of eqn.(4). This equation represents the actual torque-speed characteristics of the Darrieus wind turbine as shown in Fig.(3). The actual characteristics must be scaled to be appropriate for the considered motor characteristics. Knowing the ratings of the motor simulator (50V, 3A, 2000rpm), the motor full load torque is calculated. Referring to Fig.(3), the turbine peak torque is equated by the calculated full load torque of the motor. Then, the torque axis is then scaled accordingly, whereas the values of n and U remains as shown in Fig.(6).

To obtain the wind turbine reference model, eqn. (4) is fitted using the scaled torque-speed characteristics, shown in Fig.(6), resulting the following equation:

$$I_{ref}(k) = c_2 n^2(k) + c_1 n(k) + c_0 \qquad (5)$$

$$I_{ref}(k) = f(n, n^2) + c_0$$

This reference model is used to estimate the reference armature current. Accordingly, the motor torque follows that of the real wind turbine system. As shown in Fig.(6), the right part of the curve is fitted where the system behaviour is stable. The first and second terms on the right side of eqn.(5), $f(n,n^2)$, are determined by the motor speed and could be used to follow the characteristic of the simulated wind turbine at each wind velocity. This is achieved by varying the equation parameters c_2 and c_1. The third term, c_0, allows for changing the no-load motor speed, which represents the wind velocity U. This term is adjusted by the wind velocity reference, U_{ref} and the scaled coefficient K_{ref}, to give the desired wind velocity. The components of the reference model are as shown in Fig. (5).

For a wind velocity and turbine speed of 11m/s and 1100 rpm, respectively, the coefficients of eqn.(5) are:

$$c_2 = -1.66 \times 10^{-6} \qquad c_1 = 8.68 \times 10^{-4}, \text{ and } \qquad c_0 = 0.9449.$$

Technically, the data acquisition card DAQ can not handle signals larger than 5 volt. The gain of the tacho-generator, T_3, is 2v/1000 rpm, and so, the possible maximum motor speed is 2500 rpm. Consequently the previous coefficients (at U= 11m/s, and n= 1100 rpm) should be scaled before being used in the reference model program and eqn.(5) becomes:

$$I_{ref}(k) = -0.266 n_v^2(k) + 0.347 n_v(k) + 0.944 \qquad (6)$$

The LabView software through DAQ lab-pc1200 receives all the information in order to realise the reference model of Fig. (5). Once it is informed about the wind velocity U, according to the wind velocity reference U_{ref} and the sampled dc motor speed n_v, it calculates the reference current I_{ref} for ANN inverse model as shown in Fig. (5).

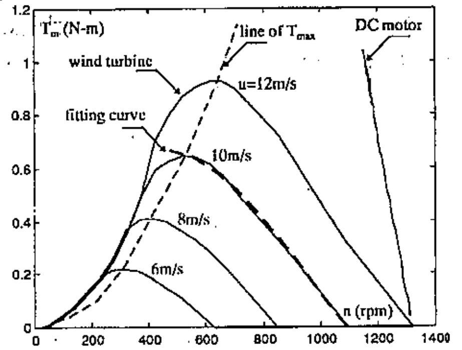


Fig.6: Torque-speed curves of the scaled, fitted wind turbine and DC motor.

4-2. ANN inverse model and structure

In general, the dc drive systems are non-linear and have some parameter uncertainties such as the magnetic field and the armature reaction. Designing a controller to track their dynamic behaviour is difficult. A simplified linear model may not be accurate and a controller design based on it may lead to sub-optimal performance and in some cases it may cause total instability of the drive system. The ability of ANN to learn a large class of non-linear functions is well known[8,9]. The ANN's role is to model the non-linearties and parameter uncertainties of the motor drive. This model allows mapping, at high precision, with the output of the wind turbine reference model.

The converter/motor/load model can be represented by a second order non-linear differential equation. This equation can be transformed to second order non-linear difference equation as follows[8-10]:

$$n(k) = f(n(k-1), i_a(k-1), v_c(k)) \qquad (7)$$

The above equation is used to build ANN forward model of the dc drive. The input to the ANN forward model must be n(k-1), i_a(k-1) and v_c(k) while the output, after training, must be equal to n(k). The converter control voltage v_c(k) can be obtained by modifying the ANN forward model to give the ANN inverse model as follows[10]:

$$v_c(k) = f(n(k), n(k-1), i_a(k-1)) \qquad (8)$$

The aim of the ANN inverse model is to build a control system which allows tracking of motor reference current trajectories given by eqn.(6). In this case, n(k), n(k-1), and i_a(k-1) are the inputs to the ANN inverse model and the output is the control voltage v_c(k), as shown in Fig (5).

Using a LabView software and DAQ lab-pc1200, a set of training data n_v(k), n_v(k-1), i_a(k-1), and v_c(k) is created by applying ramp-up control voltage v_c(k) to the converter firing circuit, and meanwhile another ramp-up of motor load with different rate is applied. The training data is generated to cover the possible operating parameters (such as speed, current, and reference control voltage), as shown in Fig.(7). The error between the actual control voltage v_c and the computed v_c(ANN) is used to train the ANN using the back-propagation algorithm. Five neurons in the hidden layer with tansigmoid activation function and a single neuron in the output layer also with tansigmoid activation function are used. The learning rate η is adjusted by trial and error to a value equal 0.0002. Figure (8) shows the trained neural network output, v_c(ANN), and the actual control voltage, v_c. It is clear that the ANN is trained well and this figure indicates that the ANN fits well with the non-linear inverse model of converter/motor/load.

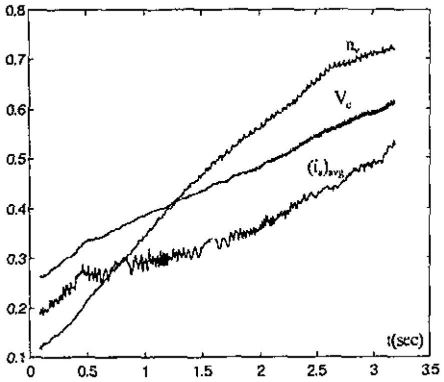


Fig. 7: The training data curves of n_v, $(i_a)_{avg}$, and v_c for ANN.

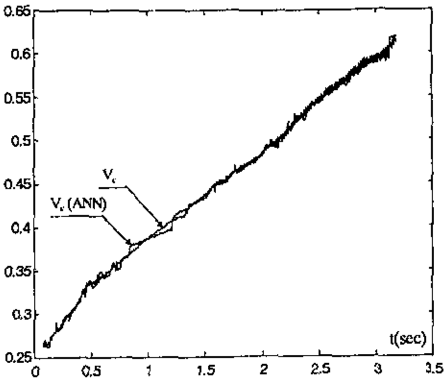


Fig. 8: Output of the ANN inverse model of trained the dc drive with ramp up of v_c.

4-3. Simulator measuring circuits

The components T_1, T_2, and T_3, shown in Fig.(4), are dedicated for the measurement and signal conditioning. T_1 is a Hall-effect voltage sensor (LV25-NP from LEM) to modulate, amplify, and isolate the control voltage signal from the D/A port of DAQ lab-pc1200 to the analog firing circuit (F.C). T_2 is a tacho-generator with gain 2v/1000 rpm and its output voltage is directly connected to the DAQ Lab-pc1200. T_3 is a Hall-effect current sensor (LA25-NP from LEM) for measuring as well as adapting the armature current to the A/D port of Lab-pc1200 for calculating the torque-speed characteristics using the LabView software.

5. Experimental Results

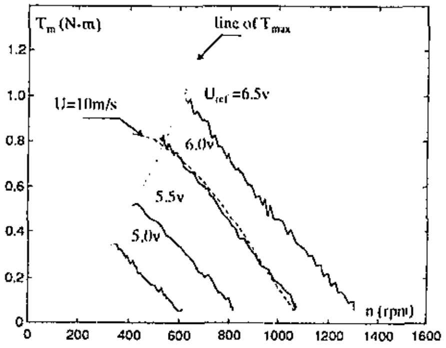
The proposed wind turbine simulator was tested at different operating conditions. Samples of the experimental results are given below.

In Fig.(9a), the steady-state torque-speed characteristics of the actual wind turbine were compared with the experimental ones of the proposed simulator, considering the wind velocity as a parameter. It is clear that, the steady state characteristics of the real wind turbine are reproduced well by the proposed simulator for different wind velocities. Also, the line of maximum torque at different wind velocities is monolithically increased and is closely similar to the maximum torque line of the wind turbine characteristics shown in Fig.(6). However, only the stable parts of the torque-speed characteristics are considered. The corresponding armature voltage variations are recorded as shown in Fig.(9b).

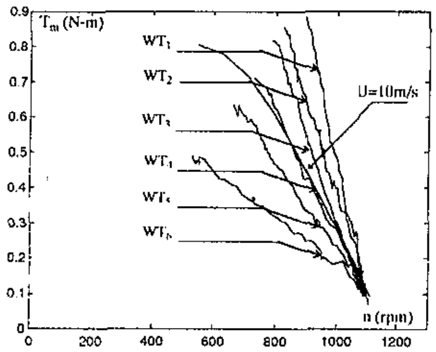
The proposed simulator can be modified to simulate other wind turbines, by modifying the parameters(c_2, c_1, and c_0) of eqn.(6) as shown in the Table. Figure (10a) shows the experimental steady-state torque-speed characteristics of the proposed simulator for different wind turbines (WT). The corresponding curves of armature voltage are shown in Fig. (10b).

parameters of (6) / wind turbine (WT)	c_2	c_1	c_0
WT_1	-0.425	0.56	1.5
WT_2	-0.37	0.48	1.32
WT_3	-0.32	0.42	1.13
WT_4	-0.26	0.34	0.94
WT_5	-0.21	0.28	0.755
WT_6	-0.13	0.17	.0.47

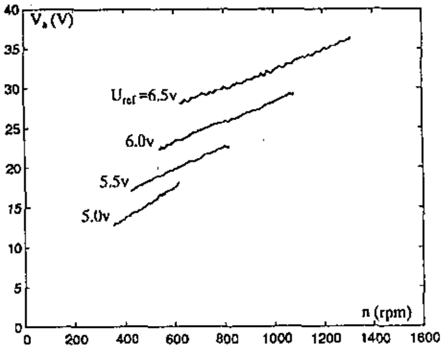
Figures (11&12) show the dynamic response of the proposed simulator for the sudden changes of reference voltage (wind velocity) and brake arm (turbine torque). Figure (11) corresponds to an increase of the reference voltage from 5.5 to 6volt, so that the motor speed increased from 650 to 900 rpm and the motor torque was increased from 0.35 to 0.4 N-m as expected from Fig.(9a). Figure(12) corresponds to an increase the brake arm with U_{ref} is 6.2volt, so that the motor speed decreased from 900 to 800 rpm and meanwhile the motor torque was increased from 0.4 to 0.45 N-m. However, the proposed simulator can track selected torque-speed characteristics in the steady state, but during transition from one to another it approaches the steady state much faster than the actual turbine. In order to achieve accurate simulation during transition, parameters of the reference model may be modified, but this results in deviations in steady-state characteristic. Further studies are still required to achieve more accurate results in dynamic cases while keeping acceptable accuracy in steady-state.



a- torque-speed

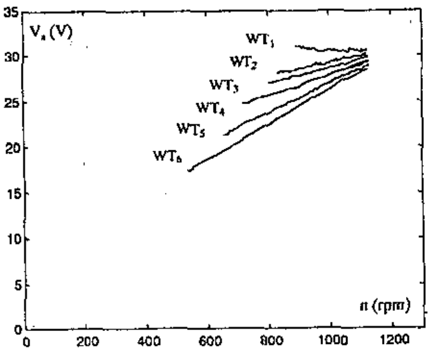


a- torque-speed



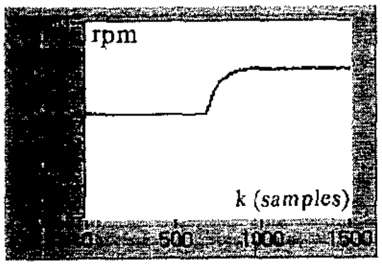
b- armature voltage-speed

Fig. 9: Experimental curves of simulator at different U_{ref}.

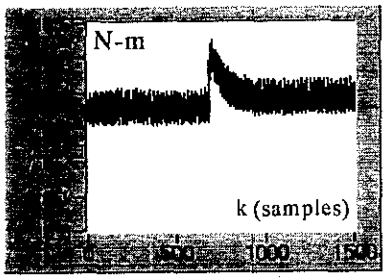


b- armature voltage-speed

Fig.10: Experimental curves of the imulator at *U= 10m/s and different* c_2, c_1, and c_0.

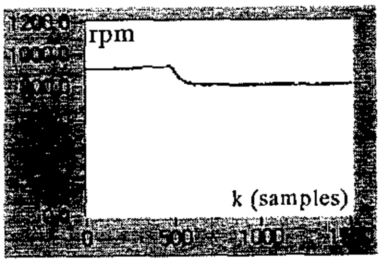


a- motor speed

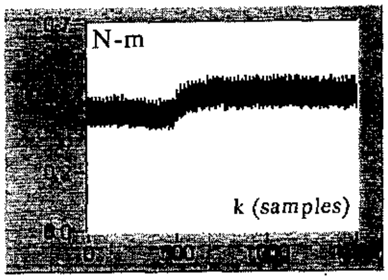


b- motor torque

***Fig. 11: Time response of the simulator* during a step change of U_{ref}.**



a- motor speed



b- motor torque

Fig.12: Time response of the simulator during a step change of load.

(time =k T, where the sampling interval T=1/150)

6. Conclusions

In this work, a small-scale wind turbine simulator has been proposed and examined. The control of this laboratory simulator has been based on ANN inverse model of a dc drive, in conjunction with the wind turbine model as a reference and a LabView software for implementation of the control algorithm. The flexibility and fast response of the dc drive employed provided accurate simulation of the torque-speed characteristics of the vertical axis wind turbine. The proposed simulator has been tested for both dynamic and steady state modes at different wind velocities and loads. It has been shown that the steady-state characteristics of the proposed simulator follow those of the actual wind turbine, satisfactorily. Nevertheless, the proposed simulator allows an easy adaptation to simulate any WECS characteristics.

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محاكي للتربينة الهوائية باستخدام آلة تسيير تيار مستمر محكومة بشبكة عصبية إصطناعية

د/ مصطفى السيد عبد الكريم

كلية الهندسة بشبين الكوم – جامعة المنوفية

ملخص البحث

عند تصميم و اختبار أنظمة توليد الطاقة الكهربية من الرياح تظهر الحاجة إلي نظام معملي للتسيير يمثل خصائص التربينة الهوائية لربطة بالألة المقترحه كمولد. و يقدم هذا البحث محاكي لتمثيل خصائص تربينة هوائية رأسية المحور بإستخدام آلة تسيير تيار مستمر يتم التحكم فيها بتدريب الشبكة العصبية الإصطناعية (**ANN**) لإستنباط نموذج مرجعي عكسي (**Inverse Model**) لهذه الآلة بحيث يقوم نظام التحكم في آلة التسيير بإجبارها علي تتبع هذا النموذج ويتوقف خرج هذا النموذج العكسي علي الإشارة المدخلة له من نموذج مرجعي (**Reference Model**) للتربينة الهوائية المراد تمثيل خصائصها.

تم بناء هذا المحاكى معمليا باستخدام محرك تيار مستمر مغذي من قنطرة ثايروستور أحادية الوجه ويتم التحكم فيه بإستخدام برنامج ال **LabView** المحمل علي الحاسب و ذلك عن طريق بطاقة إخراج وإدخال بيانات (**DAQ**)من نوع **Lab-PC1200**. وقد تم برمجة ال **LabView** لعمل نموذج الشبكة العصبية الإصطناعية العكسي لألة التسيير والنموذج المرجعي للتربينة وذلك لتمثيل خصائص تربينة (**Darrieus**) الهوائية رأسية المحور ذات قطر ١٧ متر وتعطي أقصى عزم(**$11*10^3$ N-m**) و التي تعمل عند سرعات مختلفة للرياح تصل إلي ١٢ متر/ثانية.

تم اختبار هذا المحاكي معمليا عند سرعات مختلفة للرياح وعند حالات مختلفة من التحميل للتربينة. وقد أظهرت النتائج أن هذا المحاكي يتتبع بصورة جيدة خصائص التربينة المقترحة. وتوضح النتائج أيضا قدرة المحاكي المقترح علي تمثيل أنواع أخري من التربينات الهوائية سواء رأسية أو أفقية المحور بعمل تعديل في النموذج المرجعي فقط يناسب التربينة المطلوب تمثيل خصائصها.