# Neural Control Design for Isolated Wind Generation System Based on SVC and Nonlinear Autoregressive Moving Average Approach

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*Abstract* - In this paper, the voltage and frequency control of an isolated self-excited induction generator, driven by wind turbine, is developed with emphasis on nonlinear auto regressive moving average (NARMA-L2) based on neural networks approach. This has the advantage of maintaining constant terminal voltage and frequency irrespective of wind speed and load variations. Two NARMA L2 controllers are used. The first one is dedicated for regulating the terminal voltage of the induction generator to a set point by controlling the thyristor firing angle of a static reactive power compensator (SVAR). The second one is designed to control the mechanical input power to the generator via adjusting the blade pitch angle of the wind turbine. In this application, an indirect data-based technique is taken, where a model of the plant is identified on the basis of input-output data and then used in the model-based design of a neural network controller. The proposed system has the advantages of robustness against model uncertainties and external disturbances.

The robustness of the wind-energy scheme has been certified through step change in wind speed. Moreover, the system is tested also during a step change in load impedance. Simulation results show that high dynamic performance of the proposed wind energy scheme has been achieved.

*Key-words:-* wind turbine, induction generator, NARNA-L2 controller, neural networks.

## 1. Introduction

The increasing rate of depletion of conventional energy sources has given rise to increased emphasis on renewable energy sources such as wind, micro-hydro, biogas, etc. Self excited induction generators (SEIG) are becoming popular because of their numerous advantages over alternators, specially for wind-generation of electricity in isolated places [1]. The application, dynamic behavior, and voltage stability requirements of the SEIG in wind generation were studied in many papers [2-5]. The simplest way to obtain a desired voltage at the induction generator terminals for a given speed is to provide essential capacitive reactive power excitations at different loads. The SVAR compensator, which consists of a fixed capacitor in parallel with a thyristor controlled reactor ( TCR), is the most commonly used for this purpose [6-9].

Advanced control tehniques have been proposed for regulating the voltage and frequency of a wind driven induction generator. These include output and state feedback control [10], variable structure control [11,12], $H_\infty$ control [13,14], fuzzy logic control [15], and linear quadratic Gaussian control [16].

During the past decades, the neural networks have been widely celebrated for its robustness in counteracting uncertainty perturbations. The use of artificial neural networks for nonlinear system modeling and control has proved to be extremely successful because of their ability to learn the dynamics of the plant, adaptability to a changing environment, and their robustness with respect to noise [17]. Some works have been reported on the wind-induction generator control using neural networks for regulating voltage and frequency [18, 19].

This paper presents the voltage and frequency control of a stand alone wind-driven induction generator scheme using the artificial neural network (ANN) control. This scheme consists of a wind turbine, induction generator, SVAR, and static load. The firing angle of the thyristor in the SVAR is controlled according to the error between the reference and actual load voltages. Also, the rotor speed is controlled via adjusting the mechanical power input using blade pitch-angle regulator. The complete nonlinear dynamic model of the system has been described and linearized around an operating point. The proposed control strategy has several attractive features such as robust stability against system uncertainties, disturbances, and measurment noises.

The feasibility and effectiveness of the proposed scheme have been demonstrated through digital simulations. The ANN model is carried out offline and the control algorithm does not need to perform it continuously. Therefore, the calculation burden will be only for optimization. The wind energy system with the proposed NARMA L2 controllers has been tested through step wind speed and load impedance. Simulation results show that a good damping performance has been achieved. Moreover, this scheme is robust against the parameters variation and eliminates the influence of modeling and measurement noises.

## 2. System Description

Figure (1) shows a wind energy system connected to an isolated load via a static VAR compensator. It consists of a variable pitch wind turbine, which drives a self excited induction generator. A fixed-capacitor thyristor-controlled reactor SVAR compensator is connected at the generator terminals for voltage regulation. The terminal voltage depends on the rotor speed, capacitance of the SVAR and the load impedance while the stator frequency depends mainly on the rotor speed. Therefore, if the load on the induction generator changes, or, if the wind velocity changes, there is a possibility that the terminal voltage and frequency will change. This is objectionable to sensitive loads. In this paper, the NARMA-L2 controller has been suggested to overcome this problem.

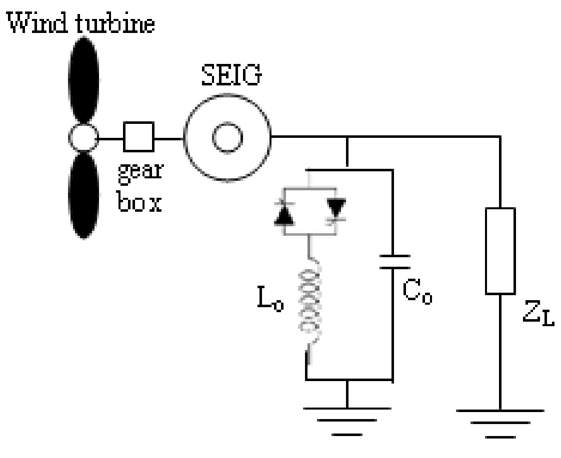


Fig.(1): Schematic representation of the wind energy system

## 3. System Dynamic Model

The complete dynamic model of the proposed isolated wind-generation system can be described as follows [13]:

$$pi_{qs} = -R_s A_1 i_{qs} - \left(\frac{i_{qs} - i_{qLo} - i_{qL}}{C_o V_{ds}} + A_2 \omega_m L_m\right) i_{ds} + R_r A_2 i_{qr} - A_1 \omega_m L_r i_{dr} \quad (1)$$

$$pi_{ds} = \left(\frac{i_{qs} - i_{qLo} - i_{qL}}{C_o V_{ds}} + A_2 \omega_m L_m\right) i_{qs} - R_s A_1 i_{ds} + R_r A_2 i_{dr} + A_1 \omega_m L_m i_{qr} - A_1 v_{ds} \quad (2)$$

$$pi_{qr} = R_s A_2 i_{qs} + A_2 \omega_m L_s i_{ds} - A_3 i_{qr} + \left(-\frac{i_{qs} - i_{qLo} - i_{qL}}{C_o V_{ds}} + A_1 \omega_m L_s\right) i_{dr} \quad (3)$$

$$pi_{dr} = -A_2 \omega_m L_s i_{qs} + R_s A_2 i_{ds} + \left(\frac{i_{qs} - i_{qLo} - i_{qL}}{C_o V_{ds}} - A_1 \omega_m L_s\right) i_{qr} - A_3 i_{dr} + A_2 v_{ds} \quad (4)$$

$$p\omega_m = (-f\omega_m + PT_m + 1.5P^2 L_m (i_{qs} i_{dr} - i_{ds} i_{qr}))/J \quad (5)$$

$$pv_{ds} = \frac{i_{ds} - i_{dLo} - i_{dL}}{C_o} \quad (6)$$

$$Pi_{qL} = \frac{1}{L}\left[-R\, i_{qL} - \left(\frac{i_{qs} - i_{qLo} - i_{qL}}{C_o v_{ds}}\right) L\, i_{dL}\right] \quad (7)$$

$$Pi_{dL} = \frac{1}{L}\left[v_{ds} - R\, i_{dL} + \left(\frac{i_{qs} - i_{qLo} - i_{qL}}{C_o v_{ds}}\right) L\, i_{qL}\right] \quad (8)$$

$$pi_{qLo} = -\left(\frac{i_{qs} - i_{qLo} - i_{qL}}{C_o V_{ds}}\right) i_{dLo} \quad (9)$$

$$pi_{dLo} = \frac{v_{ds}}{L_{eq}} + \left(\frac{i_{qs} - i_{qLo} - i_{qL}}{C_o V_{ds}}\right) i_{qLo} \quad (10)$$

## 4. Voltage Regulator

The terminal voltage of the induction generator can be regulated by controlling the firing angle α of the static VAR as described in the following differential equation:

$$p\alpha = V_{ref} - v_{ds} \quad (11)$$

Where $V_{ref}$, and $v_{ds}$ are the reference and actual voltages at the generator terminals respectively.

The above nonlinear model, which expressed by equations (1-11) are linearised around an operating point as follows:

$$px_1 = A_1 x_1 + B_1 \mu_1 + \delta_1 d_1 \quad (12)$$

Where

$x_1 = [\Delta i_{qs}\ \Delta i_{ds}\ \Delta i_{qr}\ \Delta i_{dr}\ \Delta\omega_m\ \Delta v_{ds}\ \Delta i_{ql}\ \Delta i_{dl}\ \Delta i_{qlo}\ \Delta i_{dlo}\ \Delta\alpha\ ]^t$ ,

$\mu_1 = [V_{ref}]^t$ , $d_1 = [\Delta V_m\ \ \Delta Z_L]^t$ , and

$A_1 = [\, a_{ij}\,]$ is a 11 x 11 matrix containing the system.

# 5. Power Regulator

To regulate the frequency, the generator rotor speed must be controlled. The rotor speed can be regulated by controlling the turbine's output power. The power output of the wind turbine (delivered to the induction generator) can be adjusted via controlling the blade angle β of the turbine according to the following differential equation:

$$P\beta = P_{ref} - P_t \quad (13)$$

Where $P_t$ is the output power of the turbine, which is a function in the rotor speed, blade angle, and wind speed.

$$P_t = \frac{1}{2}\rho A C_p V_w^3$$

Where $\rho$ is the air density, and $A$ is the swept area by the blades [10], and

$$C_p = (0.44 - 0.0167\beta)\sin\frac{\pi(\lambda-3)}{15-0.3\beta} - 0.00184(\lambda-3)\beta$$

The value of the reference power is chosen at rated wind speed, optimal tip-speed ratio and zero blade angle. In this case the static VAR is not controlled and the firing angle $\alpha$ considered to be constant. Also in this case, the q- and d- components of the reactor current is considered as system disturbances.

The system nonlinear equations in this case can be represented by eqs (1-8) & equ 13. The nonlinear model is linearised around an operating point as follows:

$$px_2 = A_2 x_2 + B_2 \mu_2 + \delta_2 d_2 \quad (14)$$

Where

$x_2 = [\Delta i_{qs}\ \Delta i_{ds}\ \Delta i_{qr}\ \Delta i_{dr}\ \Delta\omega_m\ \Delta v_{ds}\ \Delta i_{ql}\ \ \Delta i_{dl}\ \ \Delta\beta\ ]^t$

$\mu_2 = \left[P_{ref}\right]^t$ $d_2 = [\Delta V_w\ \ \Delta Z_L\ \ \Delta i_{qLo}\ \ \Delta i_{dLo}]^t$ , and

$A_2 = [\, a_{ij}\,]$ is a 9 x 9 matrix containing the system parameters.

# 6. Narma-L2 Control

NARMA-L2 is one of the popular neural network architectures for prediction and control. The principle idea of this control scheme is to apply the input output linearization method where the output becomes a linear function of a new control input [20-25].

Basically, there are two steps involved when using NARMA L2 control: system identification and control design. In the system identification stage design, a neural network of the plant that needs to be controlled is developed using two subnetworks for the model approximation. The network is then trained offline in batch form using data collected from the operation of the plant. Next, the controller is simply the rearrangement of two subnetworks of the plant model. Computation of the next control input to force the plant output follows a reference signal is materialized through simple mathematical equation.

## 6.1 NARMA-L2 plant model identification

In this work, the NARMA –L2 architecture is applied with the aid of the Neural Network Toolbox of MATLAB software. The identification can be summarized by the flowing:

The model structure used is the standard NARMA model [17] adapted to the feedback linearization of affine system. A companion form system (control affine) is used as the identification model, i.e.:

$$\begin{aligned} y(k+1) &= f\begin{bmatrix} y(k), y(k-1),..., y(k-n+1), u(k-1) \\ ,..., u(k-m+1) \end{bmatrix} \\ &+ g\begin{bmatrix} y(k), y(k-1),..., y(k-n+1), u(k-1) \\ ,..., u(k-m+1) \end{bmatrix} .u(k) \end{aligned} \quad (15)$$

In essence, the NARMA-L2 approximate model will be parameterized by two neural networks $\hat{f}$ and $\hat{g}$ that will be used to identify the system of Eq. (15), i.e.:

$$\begin{aligned} \hat{y}(k+1|\theta) &= \hat{f}\begin{bmatrix} y(k), y(k-1),..., y(k-n+1), u(k-1) \\ ,..., u(k-m+1),\, w \end{bmatrix} \\ &+ \hat{g}\begin{bmatrix} y(k), y(k-1),..., y(k-n+1), u(k-1) \\ ,..., u(k-m+1),\, v \end{bmatrix} .u(k) \end{aligned} \quad (16)$$

The two subnetworks are used for the model approximation; NN1 and NN2 which are used to approximate nonlinear functions f and g respectively. The NARMA-L2 system identification structure of the single link manipulator is shown in Fig. 2.

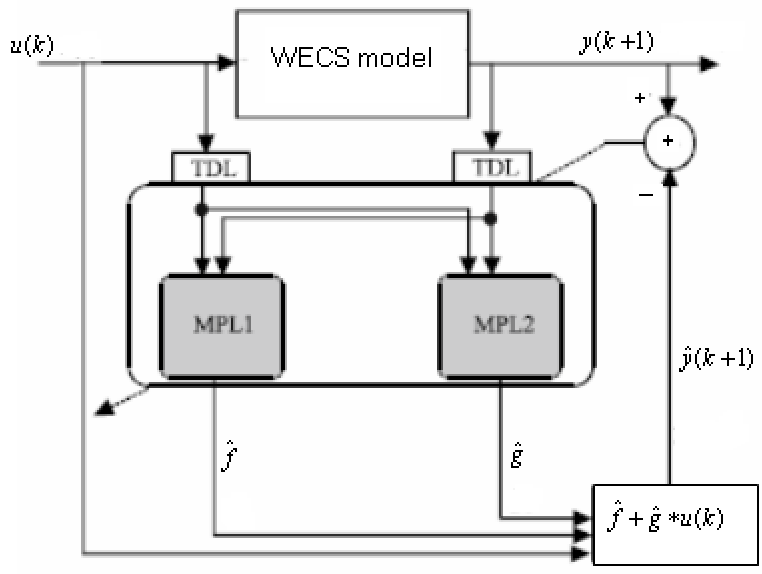


Fig. 2: NARMA-L2 plant model identification

The plant model identification in NARMA-L2 Control starts off with a dataset of input output data pairs collected using the plant mathematical model. Then, the neural nets model is trained and validated. Here, the NN1 subnetwork is a feedforward neural network with one hidden layer with p neurons of hyperbolic tangent (tanh) activation function and an output layer of one neuron with linear activation function. Also, the NN2 subnetwork is a feedforward neural network with q tanh hidden layer neurons and one output neuron.

For each subnetwork, the number of past output n and the past input m; which compose the input vector and the number of neurons (p and q) of the hidden layer are determined. Subsequently, the selected neural network structure is trained using the input pattern and the desired output from the dataset. Here, the parameters (weights and biases) of the two MLP subnetworks that properly approximate the nonlinear modeling representing the voltage regulator wind generation model and the power regulator wind generation model are estimated.

Finally, to measure the success at approximating the dynamical system plant model using the neural network model, the prediction error $e_k$ should be uncorrelated with all linear and nonlinear combination of past inputs and outputs. Thus, the validation and cross validation tests are carried out to ascertain the validity of the obtained neural network model.

## 6.2. NARMA-L2 controller design

There are two NARMA-L2 controllers have been used. The first one for terminal voltage regulator and the second one is responsible for frequency regulator. In each NARMA-L2 controller there are two neural networks have been used which are called f and g. Each one is a feed forward with three layers, i.e., an input, a hidden and an output layers. For the first controller the input layer of f network has two nodes for the terminal voltage and a bias signal of 1.0. The input layer of g network has two nodes for the $u_v$ signal and a bias signal of 1.0. And the second controller the input layer of f network has two nodes for the output power and a bias signal of 1.0 while the input layer of g network has two nodes for the $u_p$ signal and a bias signal of 1.0. The hidden layer has three nodes. The output layer has only one node for each controller. The output signal represent the $u_v$ signal for the first controller and represent the $u_p$ signal for the second controller.

The control action can be simply implemented using the obtained NARMA-L2 model based on Eq. 16 in which the functions f and g are defined. In order for a system output, y(k+1), to follow a reference trajectory yr(k+1), we set: y(k+1) = yr(k+1). The NARMA-L2 controller is designed through substituting y(k+1) with yr(k+1) in Eq. 16. Then the resolving controller output would have the form of:

$$u(k) = \frac{y_r(k+1) - \hat{f}\begin{bmatrix} y(k), y(k-1), \ldots, y(k-n+1), \\ u(k-1), \ldots, u(k-m+1) \end{bmatrix}}{\hat{g}\begin{bmatrix} y(k), y(k-1), \ldots, y(k-n+1), \\ u(k-1), \ldots, u(k-m+1) \end{bmatrix}} \quad (17)$$

Figure 3 shows the block diagram of NARMA-L2 controller which clearly a rearrangement of the NARMA-L2 plant approximated model.

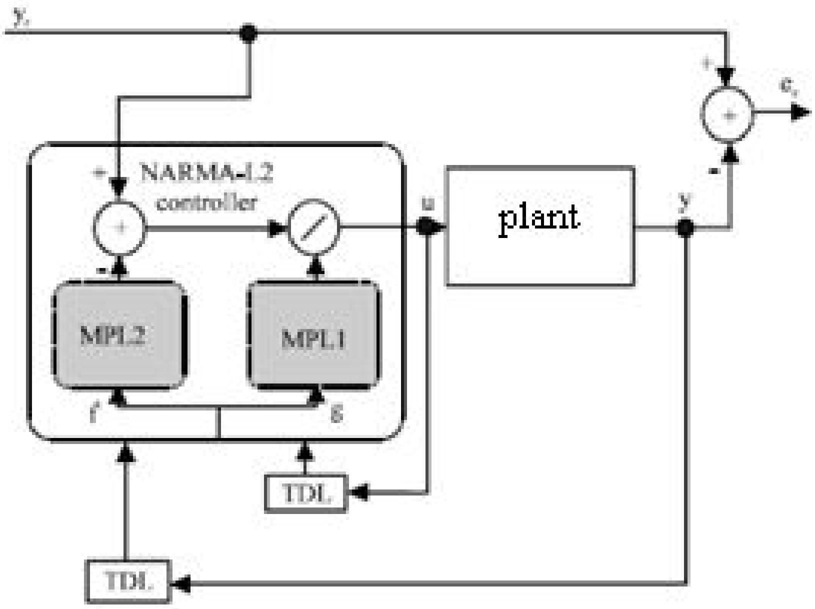


Figure (3) NARMA-L2 controller

## 7. System Configuration

The main objectives of the proposed controller are:

i) Regulating the terminal voltage of the induction generator by adjusting the thyristor firing angle of the SVAR according to the error between the reference and actual voltages, and this is the function of the first NARMA controller, and

ii) Controlling the rotor speed by changing the blade pitch angle in response to the error between the reference and actual powers, and this is the function of the second NARMA controller.

For this purpose, the controlled system has been designed to contain two NARMA controllers. The first one is designed for adjusting the induction generator terminal voltage according to a certain reference where the controller signal $u_v$ is:

$$u_v(k) = \frac{\hat{V}_{ref}(k+1) - \hat{f}\begin{bmatrix} V_{ds}(k), V_{ds}(k-1), \ldots, V_{ds}(k-n+1), \\ u_v(k), u_v(k-1), \ldots, u_v(k-m+1) \end{bmatrix}}{\hat{g}\begin{bmatrix} V_{ds}(k), V_{ds}(k-1), \ldots, V_{ds}(k-n+1), u_v(k), \\ u_v(k-1), \ldots, u_v(k-m+1) \end{bmatrix} u_v(k+1)} \quad (18)$$

The other control has been dedicated for regulating the output power to a set point, thereby, the rotor speed can be kept constant, where the controller signal $u_p$ is:

$$u_p(k) = \frac{\hat{P}_{ref}(k+1) - \hat{f}\begin{bmatrix} P_t(k), P_t(k-1), \ldots, P_t(k-n+1), \\ u_p(k), u_p(k-1), \ldots, u_p(k-m+1) \end{bmatrix}}{\hat{g}\begin{bmatrix} P_t(k), P_t(k-1), \ldots, P_t(k-n+1), u_p(k), \\ u_p(k-1), \ldots, u_p(k-m+1) \end{bmatrix} u_p(k+1)} \quad (19)$$

The block diagram of the wind energy conversion system with the proposed two NARMA L2 controllers is shown in Fig. (4). The entire system has been simulated on the digital computer using the nueral networks tool box in Matlab/Simulink software package. The specifications of the system used in the simulation procedure are listed in appendix [26-27].

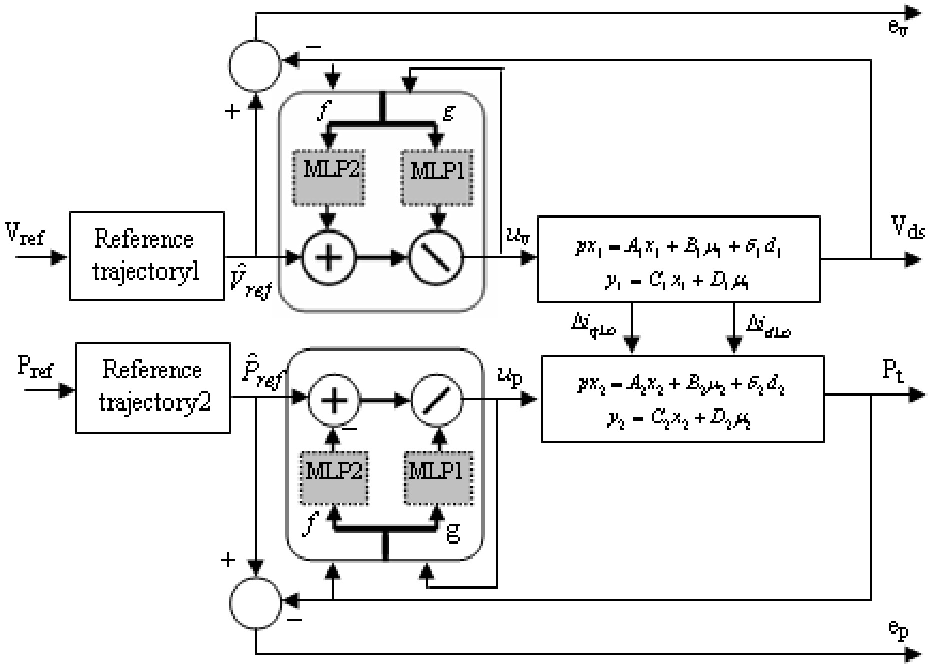


Fig. (4) : Block diagram of the wind energy conversion system with the proposed NARMA-L2 controller.

## 8. Simulation Results

Digital simulations have been carried out to validate the effectiveness of the proposed system under load and wind velocity excursions. The performance of the proposed schemes have been tested with a step change in wind speed. In addition, the system response is investigated during a step change in load impedance. Moreover, some system parameters are assumed to vary.

Simulation results depicting the variation of different variables with step change in wind speed are shown in Fig.(5). The wind speed is assumed to vary between 7.4 m/s and 8.6 m/s. It has been noticed that as the wind velocity increases, the firing angle of the thyristor will decrease. This is because, at higher wind speed, the shaft torque output of the wind turbine increases and tends to increase the rotor speed of the induction generator. The control action can be summarized as follows:

a) If the terminal voltage tends to increase due to the increase in wind speed, the first NARMA-L2 controller comes into operation and decreases the firing angle of the thyristor. This would result in reducing the equivalent inductance of the reactor in the SVAR and, in turn, increasing the reactor current. Consequently, the total effective load on the induction generator will increase. The terminal voltage tends to decrease and settles down to the reference value.

b) If the electrical frequency of the generator tends to increase due to the increase in wind speed, the second NARMA-L2 controller will increase the blade angle causing the mechanical input power to decrease. This will reduce the rotor speed and so the terminal frequency.

c) If the terminal voltage and /or frequency tries to decrease due to reduced wind velocity, the controllers will take an action which is opposite to that outlined above.

Figure (6) shows simulation results of the proposed system with step change in load impedance. It is seen that the action of the first NARMA L2 controller, with a step increase in load impedance (or a decrease in load current ) is similar to that with an increase in wind velocity and vice versa. Thus, if the load impedance is assumed to be abruptly increased, the load current will decrease. In response to the load reduction, the terminal voltage tends to rise. Therefore, the proposed first NARMA-L2 controller comes into action and decreases the firing angle of the thyristor. This is, in turn, will increase the reactor current causing the effective load on the induction generator to increase, and in turn, the terminal voltage to restore its reference.

On the other hand, if the load impedance decreases, the controller increases the thyristor firing angle which decreases the reactor current to compensate for the load increase.

The figure shows also that the change in load does not affect the rotor speed significantly. This is because the first NARMA L2 controller completes its job before the mechanical system responds to the variation.

Since our concerns are also in robust stability against various model uncertainties, some system parameters have been changed as follows:

i) The stator and rotor resistances are assumed to increase by 20% above nominal values.

ii) The moment of inertia is assumed to rise 20% above nominal.

iii) The magnetizing inductance is assumed to be 10% less than nominal.

For perturbed system the responses are shown in figs. 7 and 8. It has been indicated in the figures that the two NARMA-L2 controllers are able to stabilize the terminal voltage and frequency with high accuracy in spite of modeling errors.

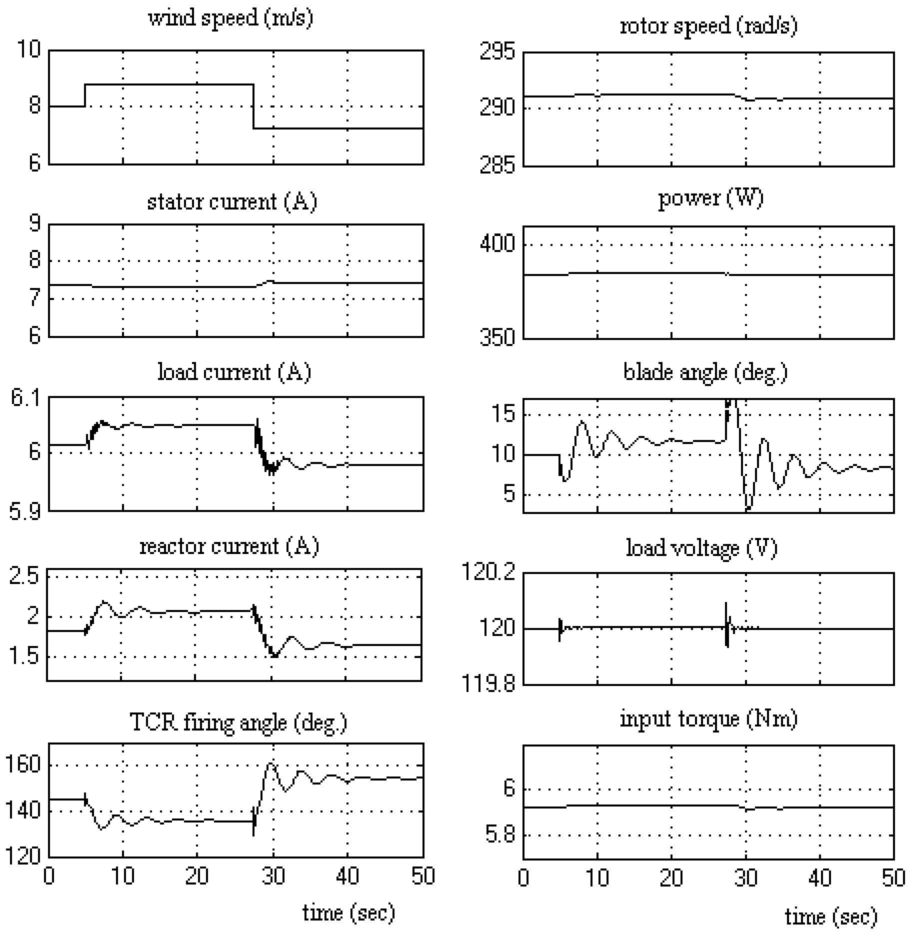


Fig. (5): Dynamic response of proposed system with step change in wind speed.

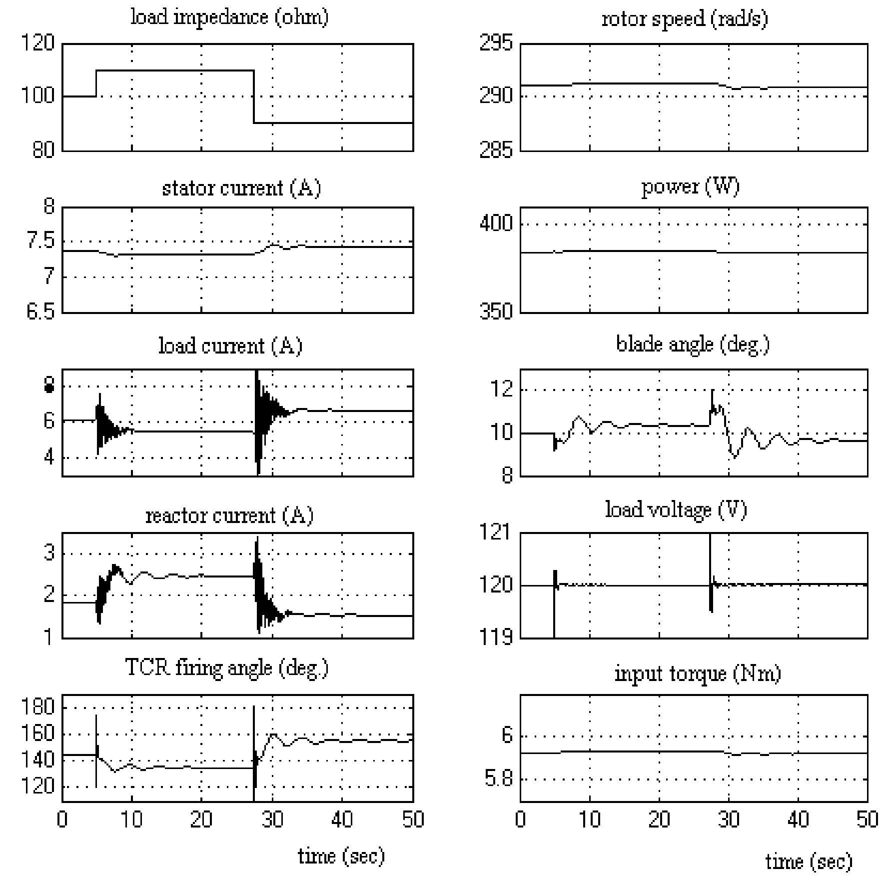


Fig. (6): Dynamic response of proposed system with step change in load impedance.

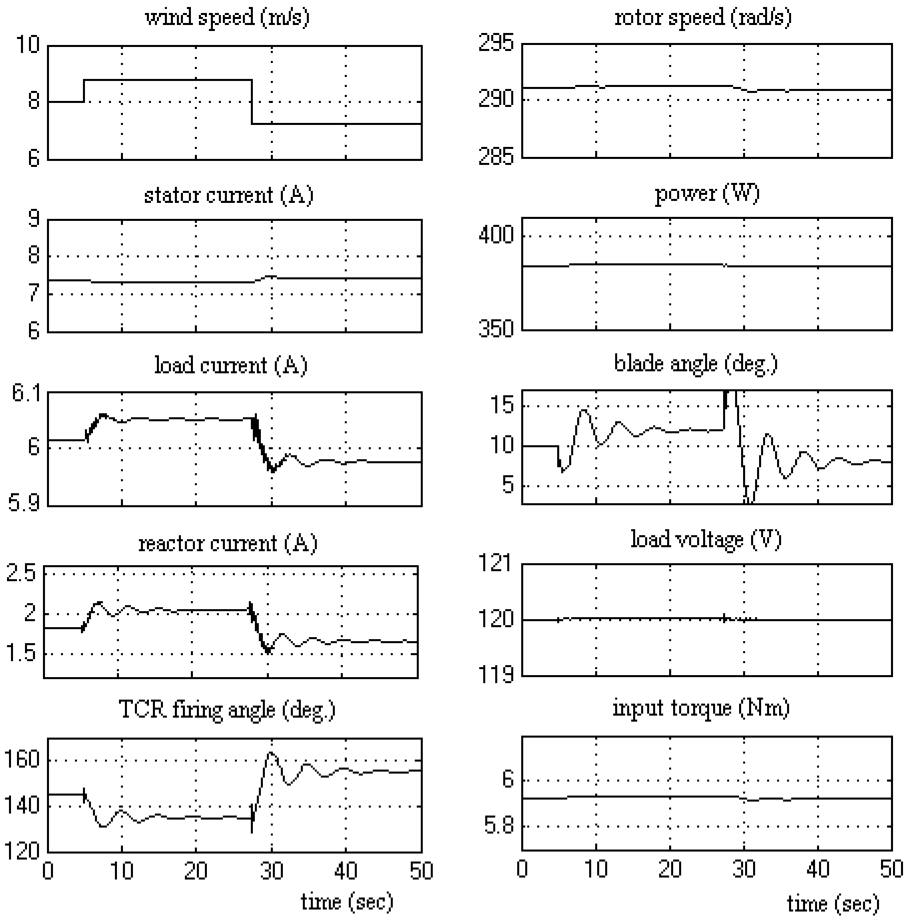

Fig. (7): Dynamic response of the proposed system with a step change in wind speed and parameters changes.

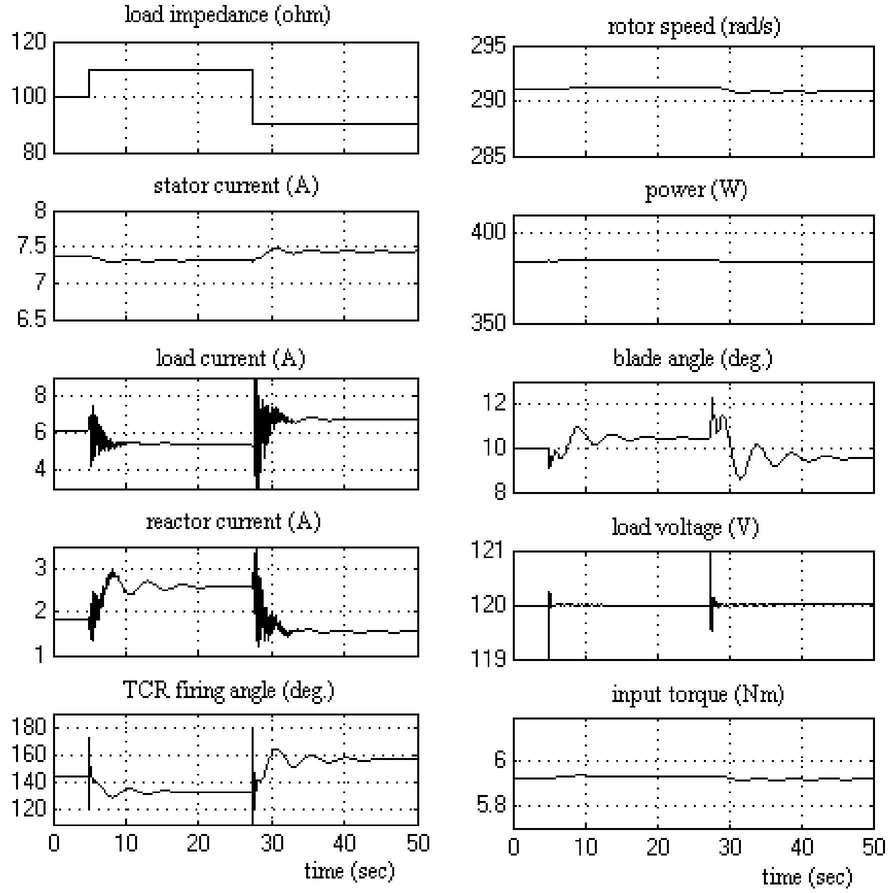


Fig. (8): Dynamic response of the proposed system with a step change in load impedance and parameters changes.

## 9. Conclusions

This paper proposes the application of NARMA-L2 to design a robust controller for regulating the voltage and frequency of a wind generation system. The controlled system consists of a wind turbine that drives an induction generator connected to an isolated load through a SVAR compensator. The terminal voltage is regulated via controlling the reactor current in the SVAR. Also, the rotor speed is adjusted by controlling the blade pitch angle. As pointed earlier and repeatedly acknowledge in a number of NARMA-L2 research papers which enjoyed their control simulations success, this controller is attractive because it requires less computation either for training the neural network and the controller design. Strategically, the controller is also simply a recomposition of the neural network plant model and the neural network training is carried out offline.

Digital simulations have been carried out in order to evaluate the effectiveness of the proposed scheme. The wind energy system with the proposed controllers have been tested through step and changes in wind speed and load impedance. The results proved that good dynamic performance, and high robustness in face of uncertainties can be achieved by means of the proposed controller.

*Nomenclature:*

$v_{ds}$ , $v_{qs}$ d-q stator voltages,
$i_{ds}, i_{qs}$ d-q stator currents,
$i_{dr}, i_{qr}$ d-q rotor currents,
$R_s$ , $R_r$ stator and rotor resistances per phase,
$L_s, L_r, L_m$ stator, rotor and magnetizing inductances
$C_0$ self excitation capacitance per phase,
$\omega_m$ angular rotor speed (electrical rads/s) of the induction generator,
$\omega_t$ angular rotor speed of the turbine,
$J$ moment of inertia,
$f$ friction coefficient,
$p$ differential operator *d/dt* ,

$L_o$ physical inductance of the reactor in the SVAR,
$\alpha$ firing angle of the SVAR,
β Turbine blade pitch angle,
$i_{dL}, i_{qL}$ d-q load current,
$i_{dLo}, i_{qLo}$ d-q reactor current in the SVAR,
λ turbine tip speed ratio,
$P$ number of pole pairs.
$V_w$ wind speed.
$C_p$ turbine power coefficient.
$\mu_v$ voltage controller signal
$\mu_p$ power controller signal

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## *APPENDIX : System parameters*

Wind turbine :

Rating : 1 kw , 450 rpm ( low speed side ) at $V_w$ = 12 m/s .

Size : Height = 4 m , Equator radius = 1 m , Swept area = 4 m2 , $\rho$ = 1.25 kg/ m2.

Induction machine :

Rating : 3-phase , 2 kw , 120 V , 10 A , 4-pole , 1740 rpm .

Parameters : $R_s$ = 0.62 Ω , $R_r$ = 0.566 Ω , $L_s$ = $L_r$ = 0.058174 H., $L_m$ = 0.054 H, $J$ = 0.0622 kg.m2 , $f$ = 0.00366 N.m./rad/s. FC-TCR : $C_o$ = 176 μF , $L_o$ = 0.127 H.