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DYNAMIC MODEL AND CONTROL OF DFIG WIND ENERGY SYSTEMS BASED ON POWER TRANSFER MATRIX USING SVPWM

B. JHANSI BAI[1] & CH. RAJESH KUMAR[2]

[1]M.Tech Student, Department of EEE, Narayana Engineering College, S.P.S.R, Nellore, Andhra Pradesh, India

[2]Associate Professor, Department of EEE, Narayana Engineering College, S.P.S.R, Nellore, Andhra Pradesh, India

ABSTRACT

This project proposes a power transfer matrix model and multivariable control method for a doubly-fed induction generator (DFIG) wind energy system using Svpwm (space vector pulse width modulation). The power transfer matrix model uses instantaneous real/reactive power components as the system state variables. The power transfer matrix model improves the robustness of controllers as the power wave forms are independent of a *dq* frameofre ference. The design controller includes six compensators for capturing the maximum wind power and supplying there quired reactive power to the DFIG. A power/current limiting scheme is also presented to protect power converters during a fault. The validity and performance of the proposed modeling and control approaches are investigated using a study system consisting of a grid-connected DFIG wind energy conversion system. This investigation uses the time-domain simulation of the study system to: 1) validate the presented model and its assumptions, 2) show the tracking and disturbance rejection capabilities of the designed control system, and 3) test the robustness of the designed controller to the uncertainties of the model parameters.

KEYWORDS: Doubly Fed Induction Generator (DFIG), Dynamics Modeling, Instantaneous Power, Multivariable Control, Wind Energy Systems, Wind Power Control, Wind Turbine Generator

I. INTRODUCTION

Wind energy conversion systems are currently among economically available and viable renewable energy systems which have experienced rapid growth in recent years. Increasing the penetration level of wind farms highlights the grid integration concerns including power systems stability, power quality (PQ), protection, and dynamic interactions of the wind power units in a wind farm [1]–[3]. Wind energy systems based on doubly fed induction generators (DFIGs) have been dominantly used in high-power applications since they use power-electronic converters with ratings less than the rating of the wind turbine generators [4]–[8]. The scope of this project is dynamic modeling and control of DFIG wind turbine generators using svpwm.

Modeling and control of DFIGs have been widely investigated based on well-established vector control schemes in a stator field-oriented frame of reference [7]–[9]. The vector control is a fast method for independent control of the real/reactive power of a machine. The method is established based on control of current components in a *dq* frame of reference using an *abc/qd0* transformation. Since the *dq* components are not physically available, the calculation of these components requires a phase-locked loop (PLL) to determine synchronous angle [8], [9]. The dynamics of *abc/qd0* transformations are often ignored in the procedure of control design. Thus, any control design approach must be adequately robust to overcome the uncertainties in estimation of machine parameters as well as unaccounted dynamics of the overall system.

Direct torque control (DTC) and direct power control schemes (DPC) have been presented as alternative methods which directly control machine flux and torque via the selection of suitable voltage vectors [3]–[4]. It has been shown that DPC is a more efficient approach compared to modified DTC [5]–[7]. However, the DPC method also depends on the estimation of machine parameters and it requires a protection mechanism to avoid over current during a fault in the system. This project proposes a modeling and control approach which uses instantaneous real and reactive power instead of *dq* components of currents in a vector control scheme.

The main features of the proposed model compared to conventional models in the *dq* frame of reference are as follows.

- **Robustness:** The waveforms of power components are independent of a reference frame; therefore, this approach is inherently robust against unaccounted dynamics such as PLL.
- **Simplicity of Realization:** The power components (state variables of a feedback control loop) can be directly obtained from *abc* phase voltage/current quantities, which simplifies the implementation of the control system. Using power components instead of current in the model of the system, the control system requires an additional protection algorithm to prevent over current during a fault. Such an algorithm can be simply added to the control system via measuring the magnitude of current. The sequential loop closing technique is adopted to design a multivariable control system including six compensators for a DFIG wind energy system. The designed control system captures maximum wind power via adjusting the speed of the DFIG and injects the required reactive power to the system via a grid-side converter.

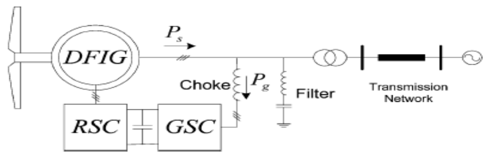


Figure 1: Schematic Diagram of the DFIG-Based Wind Generation System

II. MODEL OF A DFIG WIND ENERGY SYSTEMUSINGINSTANTANEOUS POWER COMPONENT

Definitions and Assumptions: The schematic diagram of a FIG wind turbine generator is depicted in Figure 1. The power converter includes a rotor-side converter (RSC) to control the speed of generator and a grid-side converter (GSC) to inject reactive power to the system. Using a passive sign convention, the instantaneous real and reactive power components of the grid-side converter Pg(t) and qg(t) in the synchronous *dq* reference frame, are

$$\begin{bmatrix} \mathrm{p_g(t)} \\ \mathrm{q_g(t)} \end{bmatrix} = \frac{3}{2}\begin{bmatrix} v_{sd} & v_{sq} \\ v_{sq} & -v_{sd} \end{bmatrix}\begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} \tag{1}$$

Where$u_{sd,sq}$ and$i_{gd,gq}$ are *dq* components of the stator voltages and GSC currents in the synchronous reference frame, respectively. Solving (1) for i_{gd} andi_{gq}, we obtain

$$\begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} = k_v \begin{bmatrix} p_g(t) \\ q_g(t) \end{bmatrix} \tag{2}$$

Similarly, the instantaneous real/reactive power components of DFIG can be obtained in terms of stator currents as

$$\begin{bmatrix} p_s(t) \\ q_s(t) \end{bmatrix} = -\frac{3}{2}\begin{bmatrix} v_{sd} & v_{sq} \\ v_{sq} & -v_{sd} \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \tag{3}$$

and the stator current components are given by

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = -K \begin{bmatrix} p_s(t) \\ q_s(t) \end{bmatrix} \tag{4}$$

The negative sign in (5) complies the direction of the stator power flow on Figure 1. we develop a simplified model for the DIFG-based wind turbine of Figure 1 by substituting currents in the exact model in terms of instantaneous real and reactive power. The key assumption to simplify the model is assuming an approximately constant stator voltage for DFIG. This assumption can be only used under a steady-state condition where the grid voltage at the point of common coupling (PCC) varies in a narrow interval, typically less than ± 0.05 p.u. Using this assumption, k_v is approximately constant and derivatives of currents will be proportional to the derivatives of power based on (2) and (5).

Model of DFIG Using Instantaneous Power Components: The voltage and flux equations of a doubly fed induction machine in the stator voltage synchronous reference frame can be summarized as

$$v_{sdq} = r_s i_{sdq} + j\omega_e \psi_{sdq} + \frac{d\psi_{sdq}}{dt} \tag{5}$$

$$v_{rdq} = r_r i_{rdq} + j\omega_{si} \psi_{rdq} + \frac{d\psi_{rdq}}{dt} \tag{6}$$

$$\psi_{sdq} = L_s i_{sdq} + L_m i_{rdq}, \psi_{rdq} = L_m i_{sdq} + L_r i_{rdq} \tag{7}$$

Where $r_s$and r_r are the stator and rotor resistances, and $\omega_e$is the synchronous (stator) frequency. Subscripts s and r signify the stator and rotor variable, and L_s, L_r and $L_m$are the stator, rotor, and magnetization inductances, respectively. The complex quantities v_{dq}, i_{dq} and ψ_{dq} represent the voltage, current, and flux vectors, and is the slip frequency defined as

$$v_{sdq,rdq} \triangleq u_{sd,rd} + jv_{sq,rq}, i_{sdq,rd} \triangleq i_{sd,rd} + ji_{sq,rq},$$

$$\psi_{sdq,rdq} \triangleq \psi_{sd,rq} + j\psi_{sq,rq}, \omega_{st} \triangleq \omega_e - \omega_r \tag{8}$$

where ω_r is the rotor speed of the induction machine. To obtain a model of DFIG in terms of $p(t)$ *and* $q(t)$the rotor flux and current are obtained from (8) as

$$i_{rdq} = \frac{\psi_{sdq} - L_s i_{sdq}}{L_m}, \psi_{rdq} = \frac{L_r}{L_m}\left(\psi_{sdq} - L_s^{'} i_{sdq}\right) \tag{9}$$

$$i_{rdq} = \frac{\psi_{sdq} - L_s i_{sdq}}{L_m}, \psi_{rdq} = \frac{L_r}{L_m}\left(\psi_{sdq} - L_s^{'} i_{sdq}\right) \tag{10}$$

Where $L_s^{'} \triangleq \left(1 - (L_m^2)/(L_s L_r)\right)$.Then, by substituting fori_{rdq} *and* u_{rdq} from (10) in (7) and then by solving (6) and (7) for i_{sdq}we obtain

$$\frac{d}{dt} i_{sdq} = \frac{1}{L_s^{'}} v_{rdq} - \frac{L_m}{L_s^{'} L_r} v_{rdq} + \frac{r_r - j\omega_r L_r}{L_s^{'} L_r} \psi_{sdq} - \left(\frac{r_r L_s + r_s L_r}{L_r^{'} L_r} + j\omega_{sl}\right) i_{sdq} \tag{11}$$

Using (5) to replace $i_{sd,sq}$components ofi_{sdq} in (11) and by rearranging the equation, we obtain

$$\frac{dp_s}{dt} = g_1 p_s - \omega_{sl} q_s - g_4 \psi_{sd} - g_5 \psi_{sq} + u_{rd} \tag{12}$$

$$\frac{dq_s}{dt} = \omega_s p_s - g_1 q_s - g_5 \psi_{sd} + g_4 \psi_{sq} + u_{rq} \tag{13}$$

The state equation of the stator flux can be obtained by substituting fori_{sq} *and* i_{sd} from (5) in (6). Solving the stator voltage equations for $\psi_{sd,sq}$ yields

$$\frac{d\psi_{sd}}{dt} = v_{sd} + \omega_e \psi_{sq} + \frac{2r_s}{3v_s^2}\left(v_{sd} p_s + u_{sq} q_s\right) \tag{14}$$

$$\frac{d\psi_{sq}}{dt} = v_{sq} - \omega_e \psi_{sd} + \frac{2r_s}{3v_s^2}\left(v_{sq} p_s - v_{sd} q_s\right) \tag{15}$$

The electromechanical dynamic model of the machine is

$$\frac{d\omega_r}{dt} = \frac{P}{J}(T_e - T_m) \tag{16}$$

where P,J, and T_m are the number of pole pairs, inertia of the rotor, and mechanical torque of the machine, respectively

$$T_e = \frac{3}{2}P\left(\psi_{sd} i_{sq} - \psi_{sq} i_{sd}\right) \tag{17}$$

In (17), the mechanical torque T_m is input to the model andT_e, based on (16), can be expressed in terms of instantaneous real and reactive power. Substituting for i_{sd} and i_{sd} from (5) in (18) and then replacing T_e in (17), we deduce

$\frac{d\omega_r}{dt} = g_6 p_s + g_7 q_s - \frac{P}{J} T_m$ (18) The simplified model of the induction machine is presented in (2)–(6) and (9) which the model of DFIG in (1) is a nonlinear dynamic model since the coefficients of the state variables are functions of the state variables.

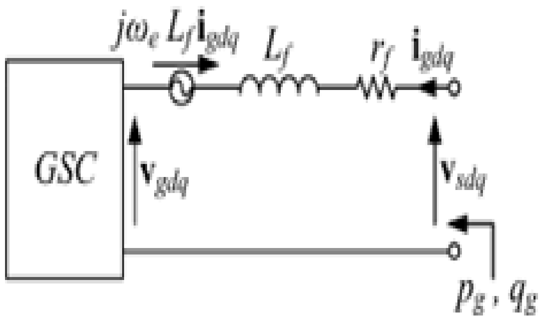


Figure 2: Equivalent Circuit of the Grid-Side Filter

$$\frac{d}{dt}\begin{bmatrix} p_s \\ q_s \\ \psi_{sd} \\ \psi_{sq} \\ \omega_r \end{bmatrix} = \begin{bmatrix} g_1 & -\omega_{sl} & -g_4 & -g_5 & 0 \\ \omega_{sl} & g_1 & -g_5 & g_4 & 0 \\ \frac{2r_s v_{sd}}{3u_s^2} & \frac{2r_s v_{sq}}{3u_s^2} & 0 & \omega_e & 0 \\ \frac{2r_s v_{sq}}{3u_s^2} & -\frac{2r_s v_{sd}}{3u_s^2} & -\omega_e & 0 & 0 \\ g_6 & g_7 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} p_s \\ q_s \\ \psi_{sd} \\ \psi_{sq} \\ \omega_r \end{bmatrix} + \begin{bmatrix} u_{rd} \\ u_{rq} \\ v_{sd} \\ v_{sq} \\ \frac{PT_m}{-J} \end{bmatrix} \tag{18}$$

Grid-Side Converter and Filter Model

Figure 2 shows the representation of the grid-side converter and its filter in the synchronous reference frame. The dq model of the grid-side converter and filter is

$$V_{sdq} = V_{gdq} + L_f \frac{di_{gdq}}{dt} + j\omega_e L_f i_{gdq} + r_f i_{gdq} \tag{19}$$

by Substituting for i_{gdq} from (2) in (20) yields

$$\begin{bmatrix} \frac{dp_g}{dt} \\ \frac{dq_g}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{r_f}{L_f} & -\omega_e \\ \omega_e & -\frac{r_f}{L_f} \end{bmatrix} \begin{bmatrix} p_g \\ q_g \end{bmatrix} + \begin{bmatrix} u_{gd} \\ u_{gq} \end{bmatrix} \tag{20}$$

The delivered real power to the rotor is

$$p_r = \frac{3}{2}\left(v_{rd}i_{rd} + v_{rq}i_{rq}\right) \tag{21}$$

III. LINEARIZED DYNAMIC MODEL OF A DFIG WIND TURBINE GENERATOR

DFIG and Wind Turbine Model: The *dq* components of the stator flux of a DFIG in a field-oriented frame of reference with$u_{sq} = 0$ can be obtained from (15) and (16) as

$$\Psi_{sd} = 0, \Psi_{sq} = -\frac{v_{sd}}{\omega_e} \tag{22}$$

the small signal model of DFIG can be

$$\frac{dp_s}{dt} = -g_1 p_s - \omega_{slo} q_s + (q_{s0} + g_s)\omega_r + u_{rd} \tag{23}$$

$$\frac{dp_s}{dt} = \omega_{sl0} p_s - g_1 q_s - p_s \omega_r + u_{rd} \tag{24}$$

$$\frac{d\omega_r}{dt} = -\frac{p^2}{j\omega_e} p_s - \frac{P}{J} T_m \tag{25}$$

The linearized dynamic model of DFIG and wind turbine in the Laplace domain yields

$$\begin{bmatrix} s + g_1 & \omega_{sl0} & -(q_{s0} + g_5) \\ -\omega_{sl0} & s + g_1 & P_{s0} \\ \frac{p^2}{J\omega_e} & 0 & s + \frac{PK_T}{J} \end{bmatrix} \begin{bmatrix} p_s \\ q_s \\ \omega_r \end{bmatrix} = \begin{bmatrix} u_{rd} \\ u_{rq} \\ 0 \end{bmatrix} \tag{26}$$

the dynamic model of DFIG and the wind turbine in Laplace domain can be expressed based on a power transfer function as

$$\begin{bmatrix} p_s \\ q_s \\ \omega_r \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \\ h_{31} & h_{32} \end{bmatrix} \begin{bmatrix} u_{rd} \\ u_{rq} \end{bmatrix} \tag{27}$$

Model of the Grid-Side Filter and DC Link: The model of the grid-side filter in Laplace domain can be obtained by transferring (21) into the Laplace domains

$$\begin{bmatrix} s + \frac{r_f}{L_f} & \omega_e \\ -\omega_e & s + \frac{r_f}{L_f} \end{bmatrix} \begin{bmatrix} p_g \\ q_g \end{bmatrix} = \begin{bmatrix} u_{gd} \\ u_{gq} \end{bmatrix} \tag{28}$$

the grid-side filter model in the Laplace domain is

$$\begin{bmatrix} p_g \\ q_g \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \begin{bmatrix} u_{gd} \\ u_{gq} \end{bmatrix} \tag{29}$$

the linearized model of dc link can be obtained as

$$\frac{dV_{dc}}{dt} = \frac{p_g - p_r}{CV_{dc0}} \tag{30}$$

the dc bus model in the Laplace domain is

$$V_{dc} = \frac{p_g - p_r}{sCV_{dc0}} \tag{31}$$

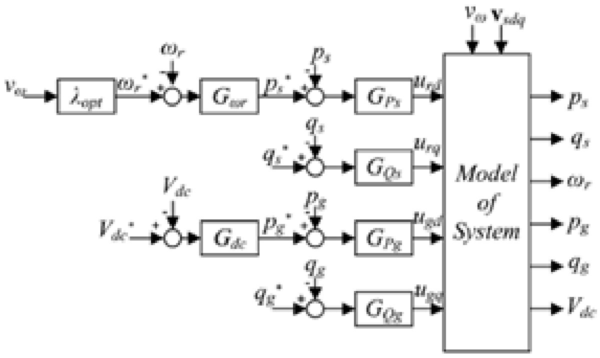


Figure 3: Schematic Diagram of the Feedback Control System for the Machine-Side and Grid-Side Converters

IV. MULTIVARIABLE CONTROLLER DESIGN FOR A DFIG WIND TURBINE GENERATOR

Controller Design Scheme: Figure 3 depicts the suggested multivariable feedback control system for the machine- and grid-side control schemes. In this scheme, the control inputs of the liberalized model of the system are (U_{rd}, U_{rq}) to control real/reactive power of the rotor and (U_{gd}, U_{gq}) to adjust the dc-link voltage and injected reactive power to the system. The sequential loop closing (SLC) method [8] is adopted to design six controllers based on the multivariable model of the system developed in Section III.

Design of the Machine-Side Controllers: Stator Real and Reactive Power Controllers; considering(u_{rd}, P_s) as the first pair in (9) and, thus, imposing g$u_{rq} = 0$ we obtain the first SISO subsystem for controller design

$$p_s = h_{11}u_{rd} \tag{32}$$

The first controller to be designed is

$$u_{rd} = G_{P_s}(p_s^* - p_s) \tag{33}$$

Substituting from (31) in (32), the closed-loop model of the first subsystem in Laplace domain

$$p_s = \frac{h_{11}G_{P_s}}{1+h_{11}G_{P_s}}p_s^* \tag{34}$$

the closed-loop model of the second subsystem is obtained

$$q_s = \frac{G_1}{1+G_2G_{Q_s}}p_s^* + \frac{G_1G_{Q_s}}{1+G_2GQ_s}q_s^* \tag{35}$$

Rotor Speed Controller: Speed control of the turbine-generator rotor is performed via control of the real power of the stator. Therefore, the speed controllerG_{ω_r} uses p_s^* as the control input. Using the control scheme of Figure 3, is p_s^*

$$p_s^* = G_{\omega r}(\omega_r^* - \omega_r) \tag{36}$$

Embedding $G_{P_s}$and G_{Q_s} controllers in the model of the system, the transfer function of rotor speed can be calculated as

$$\omega_r = G_3p_s^* + G_4q_s^* \tag{37}$$

Grid-Side Controller: Grid-Side Real and Reactive Power Controllers: The Controller design procedure for G_{P_s} and G_{Q_s} is quite similar to that of the rotor-side converter since both controllers have the same structure.

Current Limiting during a Fault: During a fault and/or sever transients, additional protection algorithms, such as fault ride through (FRT) and startup algorithms, must be added to the control system. Various algorithms, including active crowbar [3], series dynamic restorer [2], and dynamic voltage restorer [3] have been suggested for FRT. These algorithms are independent of the control approach during the normal operation; therefore, they can be used with the proposed transfer power matrix method herein as well. In addition to FRT algorithms and to mitigate over current during a transient, an extra feedback loop can be used to sense the converter currents and reduce the power reference commands during transients. This extra loop only requires.

V. SIMULATION DIAGRAM AND RESULTS

Simulation diagram the circuit as show in the below Figure 4. A. Tracking and Disturbance Rejection Capabilities: Figure 5(a) and (b) shows a trapezoidal pattern for wind speed and a step change in the reactive reference which are applied to the controllers of the study system The trapezoidal pattern was selected to examine the system behavior following variation in the wind speed with both negative and positive slopes. The selected wind speed pattern spans an input mechanical wind power from 0.7 to 1 p.u.

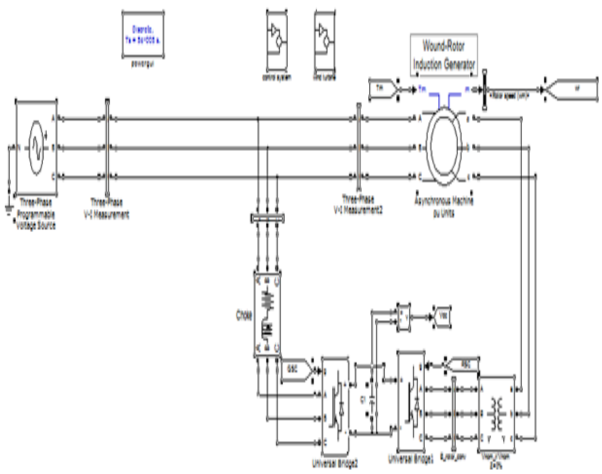


Figure 4: Simulation Circuit Diagram of the DIFG Wind Turbine Using SVPWM

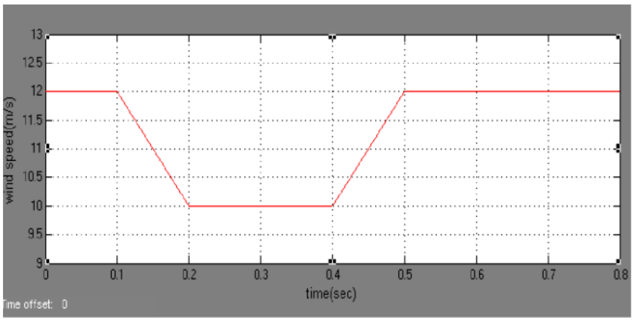


Figure 5(a): Reference Commands for Wind Using SVPWM

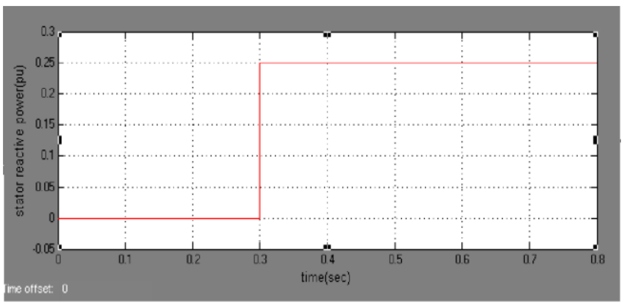


Figure 5(b): Reference Commands for the Stator Reactive Power Using SVPWM

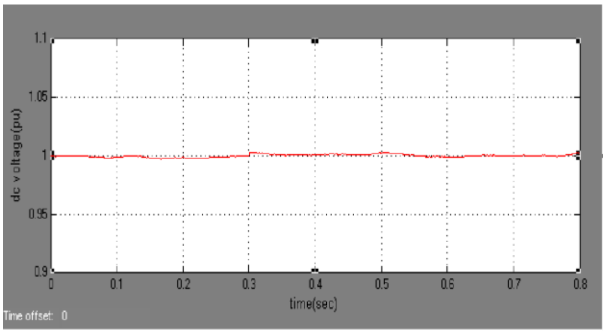


Figure 6(a): RMS Values of the Stator Voltage Using SVPWM

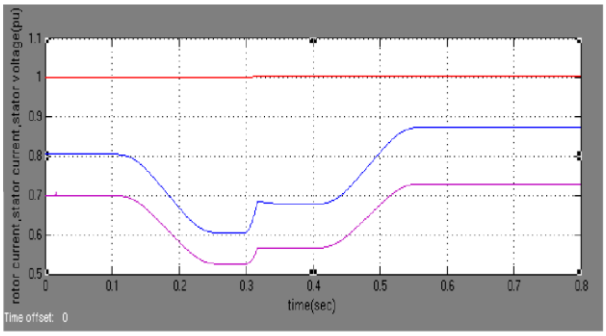


Figure 6(b): RMS Values of the Stator Currents Using SVPWM

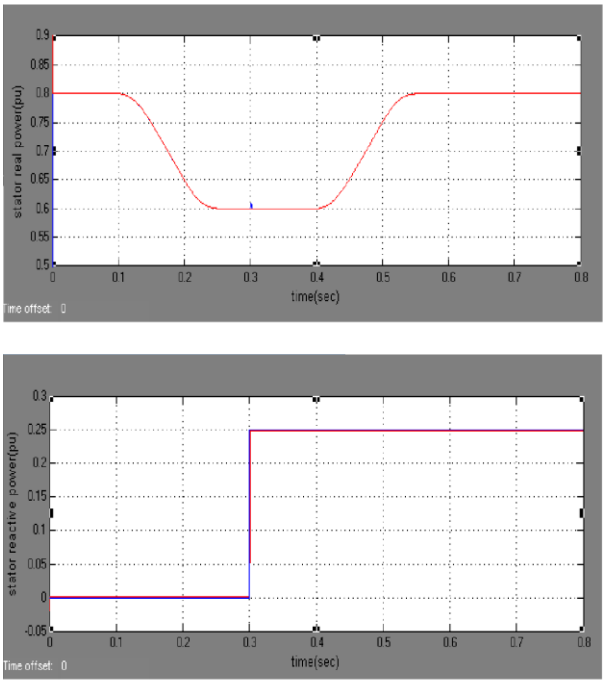
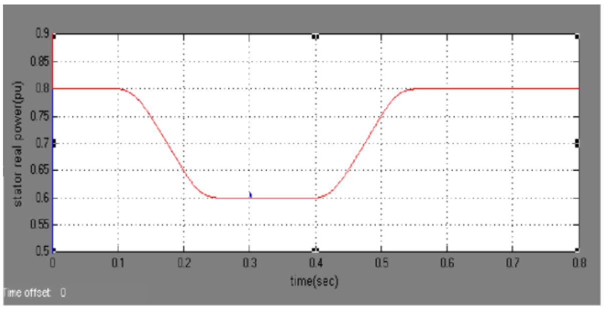


Figure 7: Tracking Performance of Real and Reactive Stator Powers Using SVPWM



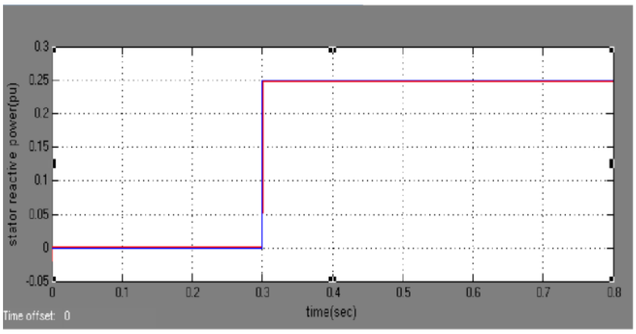
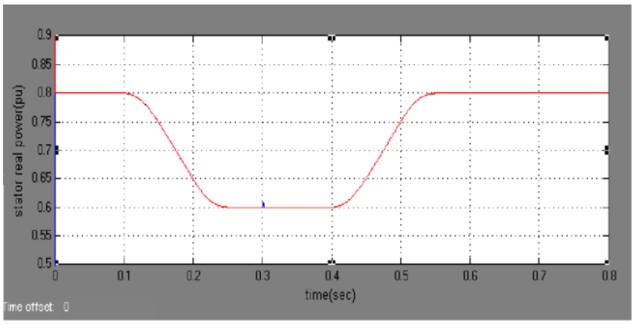


Figure 8: Robustness of the Controllers to Variations in L1 Using SVPWM



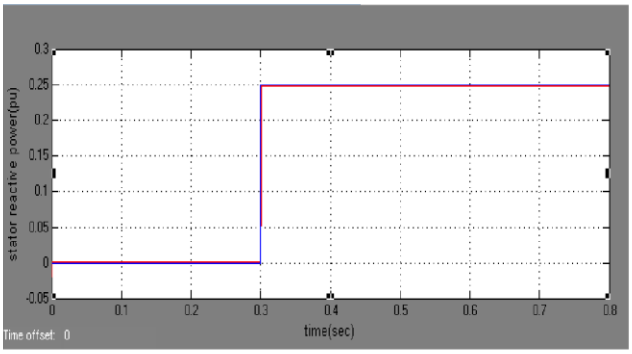


Figure 9: Robustness of the Controllers to a 40^0 Error in the PLL Angle Using SVPWM

VI. CONCLUSIONS

An alternative modeling and controller design approach based on the notion of the instantaneous power transfer matrix is described for a DFIG wind energy system. The waveforms of the power components remain intact at different reference frames and can be easily calculated using the *abc* phase voltages and currents. Therefore, this approach facilitates the implementation of the controllers and improves the robustness of the control system. Furthermore, the proposed model can be potentially used to simplify the control issues of the wind energy system under an unbalanced condition since feedback variables are independent of *qd*-components in positive, negative, and zero sequences.

The proposed approach is verified using the time-domain simulation of a study system for DFIG wind energy systems. The simulation results show that the suggested model and control scheme can successfully track the rotor speed reference for capturing the maximum power and maintain the dc-link voltage of the converter regardless of disturbances due to changes in real and reactive power references.

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AUTHOR’S DETAILS

B. Jhansi Bai received the B.Tech Degree, from Priyadarshini College of Engineering and Technology, Nellore Affiliated to JNTU Ananthapur. Present she perceive M.Tech (Electrical Power Systems) from Narayana Engineering College, Nellore Affiliated to JNTU Ananthapur. Current research interested Area are Power systems and Electrical Machines.

Ch. Rajesh Kumar received the Master degree in power electronics and drives from Sree sastha institute of engineering and technology Affiliated to Anna University Chennai, B.Tech degree from sri vidyanikethan engineering college Affiliated to Jntu Ananthapur. Ragampet Tirupathi. Currently, He is Associate professor of electrical and electronics engineering at Narayana Engineering College, Nellore, AP.