Non-Linear Model Predictive Speed Control of Six Phase Squirrel Cage Generator in Wind Energy System

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***Abstract*— Due to the intermittent nature of wind, varying wind speed causes imbalance in the current of the six phase squirrel cage induction generator (SCIG). These changes in the input signal create inbalance in the current and therefore causes deviations in the torque and flux of the generator. Therefore, this work develops non-linear model predictive control (NMPC) scheme for the generator to ensure that uncertainties in the input of the wind energy conversion system (WECS) have little effect in the quality of output power supplied to the grid. Simulation results obtained when NMPC technique was used in controlling the generator in the WECS showed the effectiveness of the aforementioned technique. The results obtained from the developed scheme were compared with those obtained when backstepping controller was used in controlling the six phase SCIG. It was observed that the developed scheme outperformed the backstepping technique in terms of electromagnetic torque by 16.844%, while a 61.1% improvement was observed in terms of settling time for the rotor flux of the developed technique over that of the backstepping. Finally, the results obtained for the DC link voltage output showed an improvement in terms of overshoot and settling time respectively.**

Keywords*— *six phase squirrel cage induction generator, wind energy system, non-linear MPC, backstepping technique, DC link voltage.

I. Introduction

Electrical energy plays an important role in the development of any nation. This is because, the level of energy consumed or generated is a great determinant in measuring the development of modern civilization [1, 2]. Recently, generating electrical energy from renewable sources to meet load demand has been regarded as an alternative to the conventional sources of energy generation [3]. To ensure improved installation of more effective wind turbines in windy zones, different types of generators and various wind turbine concepts are being developed [4]. More offshore windfarms which guarantees greater productivity are being proposed. However, hostility and remoteness of the environment which increase the maintenance cost are the major drawbacks [5]. Nowadays, the variable-speed-wind-turbine-driven-generator is mostly used due to its inherent characteristics in ensuring extraction of maximum energy from the wind. The VSWTGs can be configured into various categories based on the type of generator used [6]. These configurations include: doubly fed induction generator (DFIG), permanent magnet synchronous generator (PMSG) with full scale power converter and asynchronous generator [7]. The earliest form of generators used in wind energy conversion system for generating electric power is the synchronous generator. DFIG are also often used. However, the full scale power configurations are preferred over the DFIG configurations due to the high degree of control associated with the full scale converter [8]. The six phase induction generator also referred to as dual stator induction generator (DSIG) is now frequently used in applications such as: wind turbines and electric vehicles [4, 9]. The most desirable feature of the six-phase induction generator especially in WECS is its fault tolerant capability. This ability ensures continuous operation of the WECS whenever there is fault on the phases of the machine or on the inverter connected to the grid [10].

The DSIG configured wind turbine system is generally connected with back-to-back converter configuration which utilizes a multi-phase two level voltage source converter (VSC) at the generator side and another converter connected at the grid side for proper control [11]. A field oriented control (FOC) or direct torque control (DTC) can be incorporated to the generator side converter (GSC) for controlling the generator speed [4]. The control of the electric power flow between the grid and generator is done by proper control of the grid side converter [12].

The literature has developed different techniques for the control of the DSIG in WECS. Bendjeddou et al. [13] presented a novel control approach for dual star induction generator used in WECS. It was observed that the developed system outperformed the conventional control (PI) in terms of the measurement criterion especially during changes in the

The authors would like to acknowledge the financial support from the Ministry of Higher Education Malaysia under Fundamental Research Grant Scheme (FRGS) (FRGS/1/2021/TK0/UTM/02/86) and Universiti Teknologi Malaysia for the funding under UTM Matching Grant (Q.K130000.3001.04M15).

speed and the load. changes in the speed and the load. Iqbal and Singh [12] presented a particle swarm optimization based controllers dual-stator induction generator for WECS. The work focused on regulating DC link voltage which ensures power flow to the grid through back-to-back converters. However, there is a need for incorporation of a controller that can minimize the deviations of the reference value of the DC link voltage with the actual value obtained. Due to the limitations highlighted in the reviewed works, this work seeks to develop a robust control technique for the six phase six phase SCIG. The controller developed will be sensitive to variations in operating conditions and system operations and will also ensure good response in regulation since these characteristics are inherent in WECS.

II. METHODOLOGY

A typical variable speed WECS that comprises the wind turbine system, DSIG, IGBT based voltage source inverter, DC link capacitor and the grid network was developed in MATLAB Simulink platform.

A. Wind Speed Model

The wind profile was generated using stochastic analysis. The equation for generating the wind profile is expressed in Equation (1):

$$v(t) = v + \sum_{k=1}^{i} v_k \sin(\omega_k t) \tag{1}$$

The v_k illustrates the instantaneous wind speed while v depicts the average wind speed. This is generated in MATLAB using the rand function. Thus, in this study, the equation describing the wind profile variation is illustrated in Equation (2):

$$\begin{aligned} 12 + 0.8\sin(2.5v(1) - 3.14/5) \\ + 0.9\sin(4v(1) - 3.14/3) \\ + \sin(5.4v(1) - 3.14/12) \\ + 0.5\sin(2.5v(1) - 3.14/12) \end{aligned} \tag{2}$$

Equation (3) shows the model for the mechanical/ aerodynamic power that helps to ensure that optimum speed is attained. This is achieved, by properly adjusting the power coefficient.

$$P_t = \frac{1}{2} \times \rho \times A \times C_p \times v^3 \tag{3}$$

where: v represents the wind velocity, P_t illustrates power, ρ is the air density and C_p depicts the power coefficient.

B. Modelling of the Six Phase SCIG

The type of multiphase generator used in this work is the DSIG. This generator comprises of two-three phase stator windings and one rotor winding. The model of the generator was formulated by transforming the 3-phases into d_1-q_2, d_2-q_2, and the zero component as described in Equations (4-9).

$$v_{d1} = \left(r_{s1} i_{d1} - \omega_a \lambda_{q1s} + p\lambda_{d1s}\right) \tag{4}$$

$$v_{d2} = \left(r_{s2} i_{d2} - \omega_a \lambda_{q2s} + p\lambda_{d2s}\right) \tag{5}$$

$$v_{q1} = \left(r_{s1} i_{q1} - \omega_a \lambda_{d1s} + p\lambda_{q1s}\right) \tag{6}$$

$$v_{q2} = \left(r_{s2} i_{q2} - \omega_a \lambda_{d2s} + p\lambda_{q2s}\right) \tag{7}$$

$$0 = r_r i_{dr} + (\omega_a - \omega_r)\lambda_{qr} + p\lambda_{dr} \tag{8}$$

$$0 = r_r i_{qr} + (\omega_a - \omega_r)\lambda_{dr} + p\lambda_{qr} \tag{9}$$

where p illustrates the differentiation, ω_a represents the synchronous reference frame speed, ω_r is the rotor electrical angular speed, λ denotes the flux linkages, r_r depicts the per phase rotor resistance, while r_s represents the per phase stator resistance and i_{d1}, i_{d2} , i_{q1} and i_{q2} are the d-q stator currents. The electromagnetic torque (T_{em}) is also evaluated as seen in Equation (10).

$$T_{em} = \frac{3}{2} \times \frac{P}{2} L_m \left[-i_{qr}(i_{d1} + i_{d2}) + i_{dr}\left(i_{q1} + i_{q2}\right)\right] \tag{10}$$

where i_{dr} and i_{qr} are the d-q rotor currents and L_m represents magnetizing inductance.

C. Field Oriented Control of a DSIG

Generally, for variable speed WECS, the DSIG speed varies whenever there are variations in the wind speed, likewise the power obtained from the wind. The GSC are controlled to ensure maximum power extraction at different speed values. Field oriented control (FOC) technique was employed for control of the generator speed. This is done by independently controlling the torque and flux. In the FOC technique, the generator currents (i_{ds} and i_{qs}) are respectively the flux and torque components. Using the park transformation theory, the control laws of the FOC approach was obtained from the generator equations. This is achieved by aligning the d-axis flux linkages with that of the rotor flux linkage vector and setting flux linkages in the q axis to zero.

Therefore, to implement the FOC into the six phase SCIG, the rotor phase's equation is expressed in Equation (11).

$$r_r i_{qr} + (\omega_a - \omega_r)\lambda_r = 0 \tag{11}$$

Doing this ensures that the electromagnetic torque and the flux are been successfully decoupled. Thus, Equations (12)-(14) were used to adequately describe the behavior of the generator:

$$i_{dr} = \frac{\varphi_r^*}{L_m + L_r} - \frac{L_m}{L_m + L_r}(i_{ds1} + i_{ds2}) \tag{12}$$

$$i_{qr} = -\frac{L_m}{L_m + L_r}\left(i_{qs1} + i_{qs2}\right) \tag{13}$$

$$\omega_{sl}^* = \frac{r_r L_m}{L_m + L_r} \times \frac{i_{qs1} + i_{qs2}}{\varphi_r^*} \tag{14}$$

where L_r illustrates the per phase rotor leakage inductance, and φ is the flux, The values selected for the parameters of the generator are as seen in Table I.

D. Cost Function

The objective function used is formulated as the summations of the deviations between the reference and actual d-q axis currents, presented in Equation (15).

$$\begin{aligned} J = \| i_d^*(k+1) - i_d^p(k+1) \|^2 \\ + \| i_q^*(k+1) - i_q^p(k+1) \|^2 \end{aligned} \tag{15}$$

$$x = \begin{bmatrix} -\frac{r_1}{L_1} & 0 & 0 & 0 & 0 \\ 0 & -\frac{r_1}{L_1} & 0 & 0 & 0 \\ 0 & 0 & -\frac{r_1}{L_1} & 0 & 0 \\ 0 & 0 & 0 & -\frac{r_1}{L_1} & 0 \\ \frac{r_r L_m}{L_m + L_r} & 0 & \frac{r_r L_m}{L_m + L_r} & 0 & \frac{r_r L_m}{L_m + L_r} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{L_1} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L_2} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{L_2} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \end{bmatrix} + \begin{bmatrix} x_2 + \frac{\tau_r}{L_1}\left\{\frac{r_r L_m (x_1 + x_2)}{L_m + L_r}\right\} \\ -x_1 - \frac{1.2}{L_1} \\ x_4 + \frac{\tau_r}{L_1}\left\{\frac{r_r L_m (x_2 - x_4)}{L_m + L_r}\right\} \\ -x_3 - \frac{1.2}{L_1} \\ 0 \end{bmatrix} [u_6] \tag{16}$$

TABLE I. PARAMETERS OF THE DUAL STATOR INDUCTION GENERATOR

S/N	Parameters	Value
1.	number of poles	2
2.	per phase stators resistances (r_s) (2)	0.008 Ω
4.	per phase rotor resistance (r_r)	0.007 Ω
3.	per phase stators leakages inductances (L_s) (2)	0.134 mH
6.	per phase rotor inductance (L_r)	0.067 mH
5.	magnetizing inductance (L_m)	0.0045 H
8.	Inertia	30 kg.m^2

where: $i_d^* q(k+1)$ and $i_{dq}^p(k+1)$ represents the d-q axis reference and predicted currents in the dynamic reference frame while $\|.\|$ represents the magnitude of the vector, J represents the objective function.

E. NMPC Scheme for A six phase SCIG

A multivariable control technique based on nonlinear model predictive control algorithm for the control of the six phase SCIG is discussed in this subsection. The performance indices that ensures the capturing of maximum energy and improvement of the overall efficiency are the flux, torque, speed and the stator currents.

In designing NMPC for the control of any system, the plant model is quite essential in predicting the future behavior of the WECS. The state space model of the DSIG was employed in this study. This model was derived from the Equations (4)-(15), to form a matrix. These equations are then expressed in Equation (16) where x_1, x_2, x_3, x_4, x_5 and x_6 represent the i_{d1}, i_{q1}, i_{d2}, i_{q2} and *flux* respectively, while u_1, u_2, u_3, u_4 and u_5 represent v_{d1}, v_{q1}, v_{d2}, v_{q2} and *zero* respectively. u_6 represents the speed (omega) and was modelled as the measured disturbance. u_1 to u_5 serves as the inputs, the d_q axis currents are the states while the measured disturbance is represented with u_6.

Efficient control of the generator speed and torque were ensured through the incorporation of the NMPC into the FOC technique. The parameters of the NMPC are as shown in Table II.

TABLE II. PARAMETERS OF THE NMPC

Parameters	Values
Sample time	0.10
Control horizon	5.00
Prediction horizon	10.00
Weights	[0.10;0.10;0.10;0.10;0.10]

F. Grid Side Control

The output power from the generator is generally transferred to the grid connected side of the WECS. The DC link voltage is regulated via optimized controller. The DC link voltage can be expressed as seen in Equation (17):

$$\frac{dU_{dc}}{dt} = \frac{1}{C}\left(i_m - i_g\right) \tag{17}$$

The reference active power in the supply network is expressed in Equation (18):

$$P^* = u_c(i_m - i_c^*) = P_{dc-m} - P_{dc}^* \tag{18}$$

where:

$$i_c^* = PI(u_c^* - u_c) \tag{19}$$

G. Optimization of the Grid Side Converter Using Cuckoo Search Algorithm

A PI controller was incorporated into the grid side converter system of the WECS, to ensure proper control of the DC bus voltage. A cuckoo search algorithm was used for optimizing the PI controller in order to obtain optimal values of the controller parameters. The algorithm ensures that optimal values of the PI controller are obtained in order to ensure constant DC link voltage during disturbances (sudden changes in the wind speed). Its parameters are as shown in Table III.

TABLE III. PARAMETERS INITIALIZATION

S/N	Simulation Parameters	Values
1	Control Probability	$0 \le pa \le 0.25$
2	Number of iterations	50
3	Population size	15
4	Step size of the nest	$0.01 \le \alpha \le 1$
5	Probability	0.255

III. Result Comparison of the NMPC Control of the WECS with that of Backstepping Control

The performance of the NMPC based model and backstepping mode control were evaluated through the DSIG speed, electromagnetic torque, direct rotor flux, DC link voltage, grid active power and current obtained when the WECS was operated in the wind profile shown in Fig. 1.

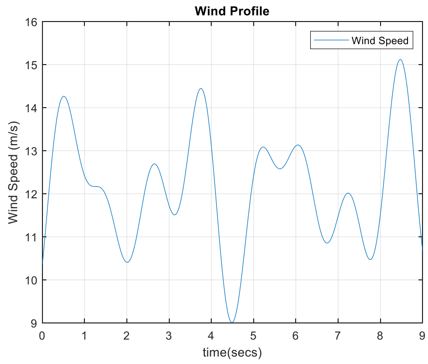

Fig. 1: The Wind Speed Profile

Fig. 2 shows the plot of generator speed variation over time, obtained from both the NMPC and backstepping mode controlled WECS. The generator speed obtained for both techniques properly track the reference as there were no deviations between the reference generator speed and the actual generator speed obtained.

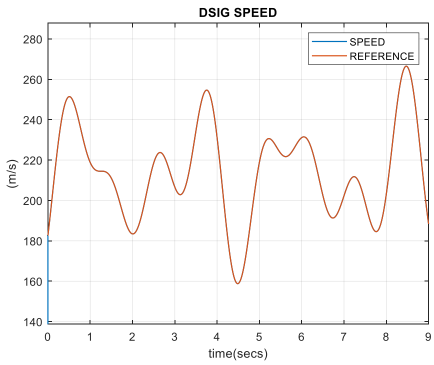

Fig. 2: DSIG Speed Plot of the WECS Using NMPC and BSC

Figs. (3a) and (b) show the electromagnetic torques against time obtained for the generator when NMPC technique and backstepping technique were used respectively. The results showed that the NMPC scheme outperformed the backstepping technique in terms of tracking.

The rotor flux obtained from the NMPC and Backstepping controlled SPIG are as shown in Figs. 4 (a) and 4 (b) respectively. It is observed from the plots, that the rotor flux settling time for the NMPC controlled SPIG was 0.7 seconds, while that of the backstepping controller is 1.8 seconds.

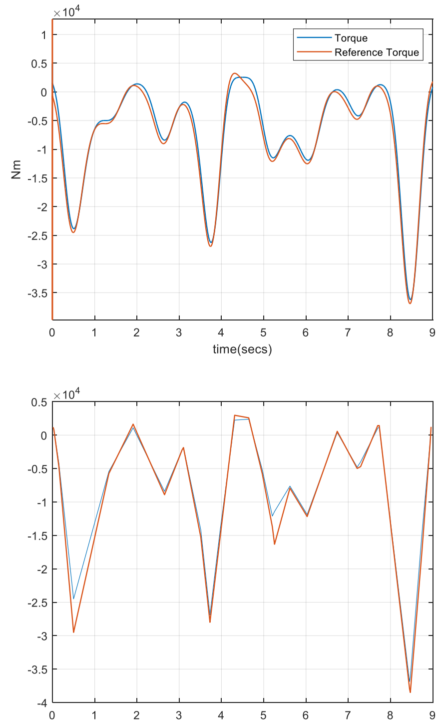

Fig. 3 (a) and (b): Electromagnetic Torque Plot for NMPC and Backstepping Algorithm

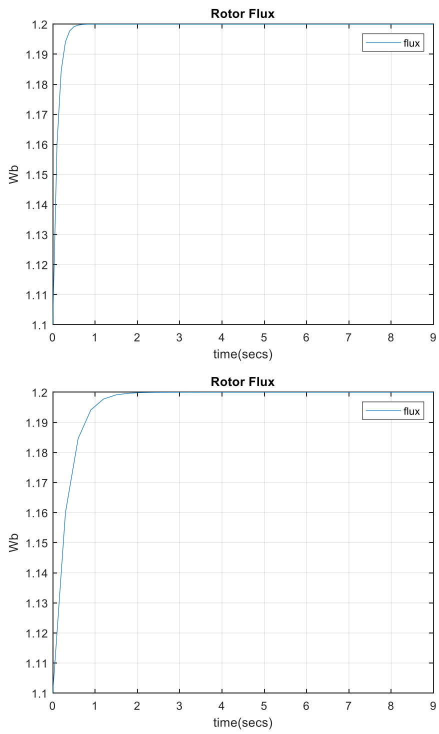

Fig. 4 (a) and (b): Rotor Flux Plot for NMPC and Backstepping Technique

Fig. 5 shows the plot of DC link voltage against time. The figure contains the reference DC link voltage, the DC link voltage obtained from the optimized PI controlled WECS and the DC link voltage obtained when trial and error technique was utilized in obtaining the values for the PI controller.

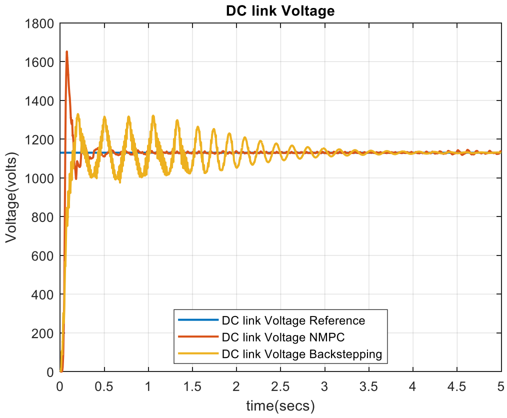

Fig. 5: Comparison of the DC link voltage Outputs

IV. Conclusion

This study presents the development of a nonlinear MPC scheme for speed control of six phase squirrel cage induction generator in WECS. The turbine of the system is connected to the grid via the SPIG, which is now increasingly used in high power systems. Simulation results obtained showed the effectiveness of the technique in terms of tracking, disturbance rejection and regulation. The results obtained from the developed scheme was compared with those obtained when backstepping controller was used. It was observed that the developed scheme outperformed the backstepping technique in terms of electromagnetic torque by 16.844%, while a 61.1% improvement was observed in terms of settling time for the rotor flux of the developed technique over that of the backstepping method.

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