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Priyanka Verma
Department of Electrical Engineering, National Institute of Technology

Kiran Kumar Jaladi
Department of Electrical Engineering, National Institute of Technology

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Model Predictive and Direct Voltage Control for Standalone DFIG System

Priyanka Verma[1,*], Kiran Kumar Jaladi[1]

[1]Department of Electrical Engineering, National Institute of Technology, Kurukshetra, Haryana, India

*Author to whom correspondence should be addressed:
E-mail: *Priyankver126@gmail.com*

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Abstract: The Doubly-fed Induction Generator (DFIG) is capable of operation in regions with varying speeds. The need for DFIG systems that supply energy to isolated loads while being powered by wind turbines at varied speeds is growing, and more studies are being done on the without grid mode i.e. Standalone mode. The DFIG's terminal bus in stand-alone mode is linked to an isolated load, and the control strategy regulates the voltage and frequency of the scaled value. There haven't been many investigations on tying the DFIG to the DC grid. However, there are still some issues with it. Large torque oscillations are one of the issues. It is caused by the nonlinear diodes connected at the stator side of DFIG. To overcome this issue, many control techniques have been proposed and developed. Among various control techniques, direct torque control (DTC) is a very popular and effective technique that is widely used. In this article, model predictive control (MPC) is integrated into a standalone DFIG to evaluate the system's performance. On the stator side of the DFIG, the MPC control approach is used, and on the rotor side, the voltage control technique. The proposed MPC-based standalone DFIG has been designed and verified in the MATLAB/Simulink environment. The results obtained are presented in this paper which shows the enhancement in the system. The value of the speed is 147 rad/sec and the electromagnetic torque is of the value of 2N-m the reference value and the obtained value are tracking each other.

Keywords: direct torque control (DTC); DC generator; model predictive control (MPC); voltage control (VC)

1. Introduction

There are several problems associated with conventional energy resources, such as toxic gases, waste dumping issues, and non-replenishable. Therefore, it is very necessary to look for alternative sources of power production, popularly known as renewable sources of energy.[1–3] The sun, wind, hydro, and biogas come under the category of renewable resources. Different machines are designed and developed for power generation to extract quality power and make the system more efficient. DFIG is one of the machines which is widely used for power generation from the wind. Standalone and Grid modes are discussed in [4] DFIG in standalone mode is designed and modeled for analyzing its performance.

In Wind energy the grid is connected to the generators and various types of generators are discussed in [5,6]. Here in [7]DFIG is the most recommended varying speed WECS due to its lower rating of the converter need. Because of its better utilization of the rotor power than comparable machines of the same machine rating, the DFIG produces more power. In [8], a study of the DTC scheme for DFIG is done. Due to the nonlinearity nature of the diode rectifier, the torque ripples are studied and three different techniques are proposed to overcome the issue. The first is field-oriented control, the second is Direct Torque Current control, and the third is Direct Torque flux control. In [9], the fuzzy logic control-based DTC technique is proposed for battery energy-based DFIG systems. By this method, unwanted harmonics and unbalanced load currents are minimized.[10] includes a discussion of the main controller topologies and techniques for grid and generator converters.[11] uses two concurrent loops to keep the stator voltage frequency and magnitude constant regardless of load variations or sporadic supply power. The required feedback is provided to the controller by the voltage sensor and speed sensorless algorithms. [12] A fuzzy logic controller (FLC) is used and thoroughly researched in order to accomplish the desired goal. In [13], the inherent nonlinear behavior of the conventional DFIG is minimized

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by inserting an adaptive MPC structure and auto-regressive moving average model. In [14], the 2 MW DFIG is used for analysis purposes. Here, the DTC is adopted for voltage and frequency control of the wind system. The Hysteresis controller is connected to the rotor and load side of DFIG to reduce the current errors by minimizing the differences between actual and reference values.[15,16]It is found that rotor current output is quite good and harmonic suppression in stator current and voltage dips reduce. In [17]MPDC is used over conventional vector control in the DFIG system. The proposed method regulates the rotor current by optimizing the voltage vector and also rid of the high-power converter switching losses. The dynamic and steady-state performance of DFIG under the low switching frequency operation. In [18], Model predictive control along with Direct power control is implemented in the DFIG machine. Here, the conventional MPDPC (model predictive direct power control) is unified with the multiple vectors MPDPC, and the overall complexity of a system is reduced. The current and power distortions are reduced under balanced and unbalanced networks. In [19], the Fake Algebraic Riccati equation (FAKE) is introduced in research for control system stability. It is designed on Simulink for validation. Here desired control and prediction horizons are selected based on the steady-state error and computational costs. In [20] Finite control set MPC with droop control is proposed for the primary frequency response of the microgrid. Here, the grid side converter of DFIG is connected to the finite control set MPC, and maximum power tracking is done at the rotor side converter of the DFIG. In [21] standalone DFIG, provided a better voltage vector control method based on predictive current control (PCC). In [22] a standalone DFIG is used along with the DTC control technique. The torque controller is preferred for the DC voltage regulations. Additionally, by maintaining a consistent DC voltage to flux ratio, the stator frequency is kept at its specified frequency, which lowers the cost and maintains an accurate position of sensors. In (Misra and Jain 2017), the system is designed to make it independent from stator side sensing, and it is done by calculating the output DC link voltage and the rotor circuit currents. In-depth mathematical calculations are done, including dominant harmonics. The DFIG-based system is found to be suitable for the variable speed DC power generation system.[24] provides an enhanced direct torque resonant control-based DC voltage ripple suppression approach for a freestanding DFIG-DC system. In [25], the standalone DFIG system is designed with and without transformers between the stator and rectifier. The control phenomenon is decided by the variation of reactive rotor current, which is used for maintaining the DC-link voltage, and the variation of active stator current is decided by the active rotor current. In [26] the mathematical modeling for a based system is designed to eliminate the fifth and seventh harmonics, which are very much dominant in nature. In [27], the mitigation of torque ripples is the prime objective, and it is done for a DFIG-based system. To reduce the ripples, the predictive control algorithm and disturbance compensation parameter are included in the estimation and analysis system. In [28], the linear matrix inequality- PI controller and MPC control algorithm are used for proper power management for DFIG-based wind energy systems. In [29], the novel frequency control technology is integrated into the DFIG-based network, and this control scheme has utilized the combination of Adaptive MPC and Recursive Polynomial Model Estimator (RPME). In [30] the predictive control technique is suggested for a DFIG-based system to regulate real and reactive power capabilities. In [31] the modified MPC is incorporated into a based wind energy system. Here the optimal switching state of the converter is obtained by optimizing the cost value function with current magnitude errors. In [32] multi-objective model predictive control (MOMPC) is created for better performance of DFIG. The suitable switching vector is determined by the cost function. By doing so, the overall performance of a system is enhanced. In [33] various control strategies are discussed for the standalone DFIG-DC system. A primary control objective system is created, and load voltage is regulated under steady and dynamic conditions. [10] includes a discussion of the main controller topologies and techniques for grid and generator converters. In [34] The battery energy storage system (BESS) supports the intermediate DC connection to deliver steady and uninterrupted power to customized loads despite changing wind speeds. In [35]to supply the initial power for the excitation, two approaches were described. One approach involved using a separation diode to connect energy storage to the DC-link component. The second technique made use of the magnet circuit's residual power as well as increased AC stator capacitance. [36], a unified power control technique that is used for the DFIG-DC system without determining the interconnection switch's status or altering the control strategy is suggested for islanded mode as well as grid mode.

In this work, torque and speed control of the standalone DFIG-DC System is done through the model predictive controller block implemented on the stator side, and direct voltage control is done on the rotor side. The motivation and the objective behind this approach is to minimise the cost function and minimise torque and stator side ripple current, appropriate voltage vectors and model predictive control are employed. In previous works that are related to standalone DFIG-DC systems the rotor side of the systems is controlled through various controllers and an uncontrolled stator is used but in this work stator side is controlled with the help of model predictive control to control the value of the torque and speed and the rotor side

is also control so the value of voltage can be controlled. The fuzzy logic is applied in DTC so that the proper sinusoidal currents are obtained without the ripples and the novelty is improved in the work.
This paper is divided into five sections. Section I consists of the introduction and literature review content. Section II describes the MPC operation principle necessary for controlling the DFIG-based system. Section III consists of the Modelling of Standalone DFIG Section IV proved the validation of the proposed control scheme and for the validation, Simulink results are presented. Here, the results of torque and stator side current are shown. In section V, the conclusion of the paper has been summarized including the future scope of the proposed method.

2. Model Predictive Control

The concept behind the use of the MPC technique is that it helps for building the prediction of the model. The system's overall behavior is determined by taking into account its actions, future states, and reference values. Moreover, for the actual prediction of the system behavior, the cost function and minimum cost functions are necessary to produce the actual command. It helps to control various parameters at a time with their constraints. The discrete-time modeling of the MPC-based system is designed with the help of the state space model of the same system. The necessary equations are given below:

$$x(k+1) = Ax(k) + Bu(k) \tag{1}$$
$$y(k) = Cx(k) + Du(k) \tag{2}$$

Where, x, u, and y denote the state variables, input variables, and output variables, respectively. Eq. (3) is the cost function required for the system's analysis.

$$J = f(x(k), u(k), \ldots\ldots\ldots, u(k+N)) \tag{3}$$
$$u(k) = [10\ldots\ldots.0]\, argmin\, J \tag{4}$$

Where J implies the cost function.
It is an optimization-based approach to problem-solving where the equation is solved using the most recent data at each sampling point, and the sequence continues until time k and the predicted time is time k+N. Table 1 shows the advantages of the MPC controller as compared to the linear controller on various parameters.

Table 1: Comparison table between linear and MPC controller[37)]

Parameters	Linear controller	MPC Controller
Controller design	Adjusting the values of proportional and integral gain	Define the value of the cost function
Strategies of modulation	PWM or SVM	MPC does not require Modulation stages
How to implement	Either analog or digitally controlled	Implemented digitally
Frequency of switching	Fixed	Variable
Flexibility of operation	presence of a constraint	Direct and simple restrictions included

In Figure1, the MPC-based current controller is fed to the input of the inverter. This current controller comprises prediction and cost function blocks. From the load model, the prediction of the i(k+1) term is estimated by drawing. The two main parts of the controller are the estimation block and the cost function block. The ‘g’ stands for the cost function.

The i_s from the load is fed to the prediction model and i_s^* is the reference value of the stator current. The i_s and i_s^* are used in cost function for minimizing the cost function. The output of the minimum cost function is used to decide the necessary switching states, and accordingly, the switching signal is fed to the inverter. In this way, the error is minimized.

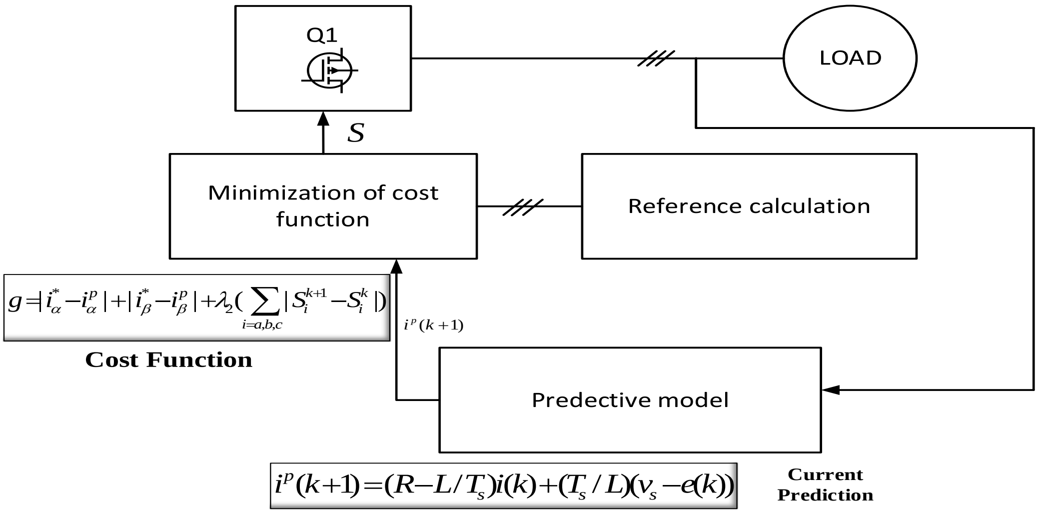

Fig. 1: A Finite control set MPC block diagram for current control

3. Proposed Control

3.1. MPC Implemented for standalone DFIG system on the stator side

The emphasis is shifting from AC power generation to DC power generation as a result of the growth in DC power applications, including the use of DC in electronic devices and other power electronic applications. Additionally, employing a partially rated converter in the SRIM management lowers the cost of generating DC power from variable speed prime. In this study, the MPC's current values are forecasted and used to assess the cost function's values. For improved outcomes, the MATLAB Simulink environment uses the MPC controller block.

3.2. Modelling of the Standalone DFIG system

For modeling a standalone DFIG system, the mathematical equations are used which are given below.

$$v_s = R_s i_s + \partial\psi_s \backslash \partial t + j\omega_s \psi_s \tag{5}$$

$$v_r = R_r i_r + \partial\psi_r \backslash \partial t + j(w_s - p w_m)\psi_r \tag{6}$$

$$\psi_s = L_s i_s + L_m i_r \tag{7}$$

$$\psi_r = L_r i_r + L_m i_s \tag{8}$$

$$T_e = (3/2) p L_m (i_{rd} i_{sq} - i_{rq} i_{sd}) \tag{9}$$

$$T_e = (3/2) p L_m / L_s (\psi_{sq} i_{rd} - \psi_{sd} i_{rq}) \tag{10}$$

$$C_{dc}(\partial v_{dc}/\partial t) = -i_{sq} + i_L \tag{11}$$

Where, ψ_s stator flux, ψ_r rotor flux, T_e electromagnetic torque, p-pole pairs, L_m magnetizing inductance, L_r rotor inductance, L_s stator inductance, $\sigma = 1 - L_m{}^2 / L_r L_s$, C_{dc} dc bus capacity, i_L load current, v_s , v_r are the rotor and stator voltage, v_{dc} dc voltage, R_r, R_s are the rotor and stator resistance.

3.3. Proposed Controllers Implemented on the Machines

In Figure2, the basic modeling of DFIG is presented. Here, the stator-side converter of DFIG is connected to the load via the MPC current controller and DC bus. This MPC current controller is the deciding factor here. This controller estimates the values based on past and present values, and based on it, the switching vectors are fed to the stator-side converter.
The power is fed to the rotor side converter through the power converter connected to the DC bus.

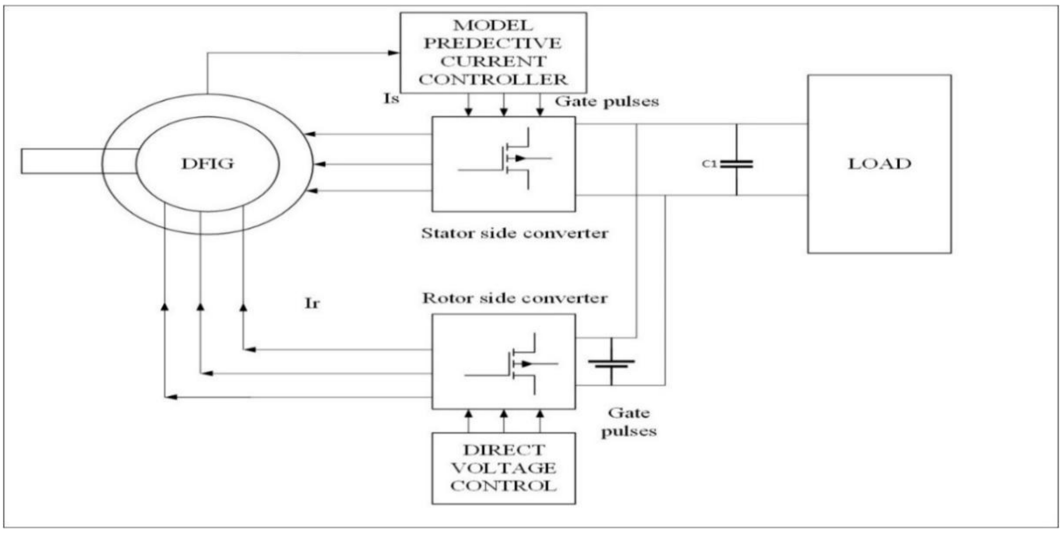

Fig. 2: Model of standalone DFIG -DC system implemented with different control strategies

For reducing the torque ripples, the direct torque control strategy is preferred and incorporated into DFIG. For this, the transfer function for rotor current is derived along with disturbances and decoupling terms. The eq. (5), (6), and (7) are substituted in eq. (6) and dq- components of rotor voltage are shown in eq. (12) and (17).

$$v_{rq} = -2L_s \backslash 3\psi_{sd} p L_m (R_r T_e + \sigma L_r (\partial/\partial t) T_e) + \omega_r \psi_{rd} \quad (12)$$

The transfer function that follows can be used to characterize it:

$$T_e(s)/v_{rq}(s) = A/s\sigma L_r + R_r \quad (13)$$
$$A = -3\psi_{sd} p L_m / 2L_s \quad (14)$$

A DC voltage regulator gives the torque reference. The torque equation assumes the following no-load circumstances and reference frame orientation with stator flow vector:

$$dv_{dc}/dt = -2T_e/3\psi_{sd} p C_{dc} \quad (15)$$
$$v_{dc}(s)/T_e(s) = 1/sB \quad (16)$$
$$B = -(3/2)\psi_{sd} p C_{dc} \quad (17)$$

A complete model of disturbances and decoupling terms is introduced in order to develop the transfer function for control of the rotor current vector d component. It is produced by adding the stator voltage equation (5) to the rotor voltage equation (6), along with the flow equations (6) and (7). Consequently, the whole control plant model, stator voltage disturbance, and control path couplings are provided by

$$v_{rd} = R_r i_{rd} + \sigma L_r (\partial i_{rd}/\partial t) + (L_m/L_s)$$
$$(v_{sd} - R_s i_{sd}) + \omega_s \psi_{sq} - (\omega_s - p\omega_m)\psi_{rq} \quad (18)$$

Assuming ψ_{sq} close to zero, the obtained equation

$$v_{rd} = R_r i_{rd} + \sigma L_r (\partial i_{rd}/\partial t)$$
$$-(\omega_s - p\omega_m)\psi_{rq} \quad (19)$$

$$i_{rd} \backslash v_{rd}(s) = 1 \backslash s\sigma L_r + R_r \quad (20)$$

The rotor current of DFIG is changed into dq- components. The calculated or measured dq-components are compared with their reference values and the differences between them are passed through the PI controller to minimize the error. The measured value of V_{dc} and its reference value are used to calculate the q-component of the rotor current. The output from PI controllers of the d and q components of the rotor current is transformed into an abc component. The switching vectors are decided by the combination of rotor currents which is obtained after the dq- abc transformation and rotor angle which is obtained from the generator speed. Fig 3 shows the voltage control scheme that is implemented on the rotor side of the converter. In this, the rotor currents and the DC voltage are taken as the reference and fed into the proportional-integral controller and after that rotor current D and q components are fed to the PI so that switching voltage vectors for PWM are obtained.

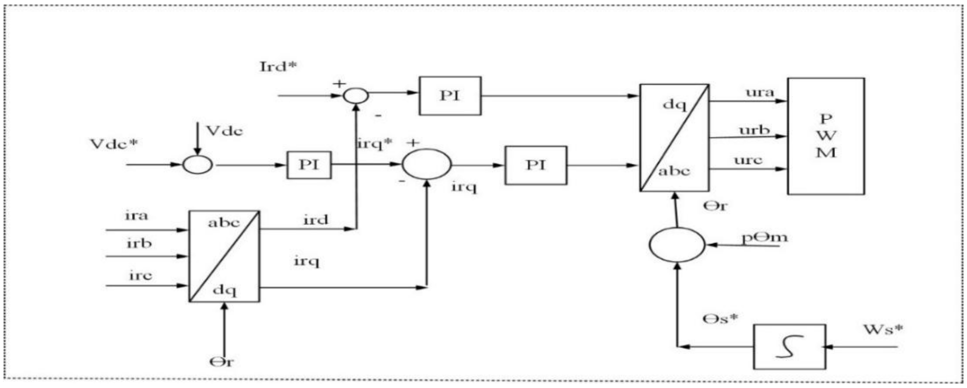

Fig. 3: Voltage control scheme implemented on the Rotor side

An additional control technique is implemented by replacing the PI with the fuzzy logic in direct torque and current control for a standalone DFIG system and the rotor side control is provided the value of DC voltage is 300V in this system and the reference is [8]. Here this method will improve the currents and it will get purely sinusoidal. In Table 2, a comparison of the proposed and traditional standalone DFIG is done.

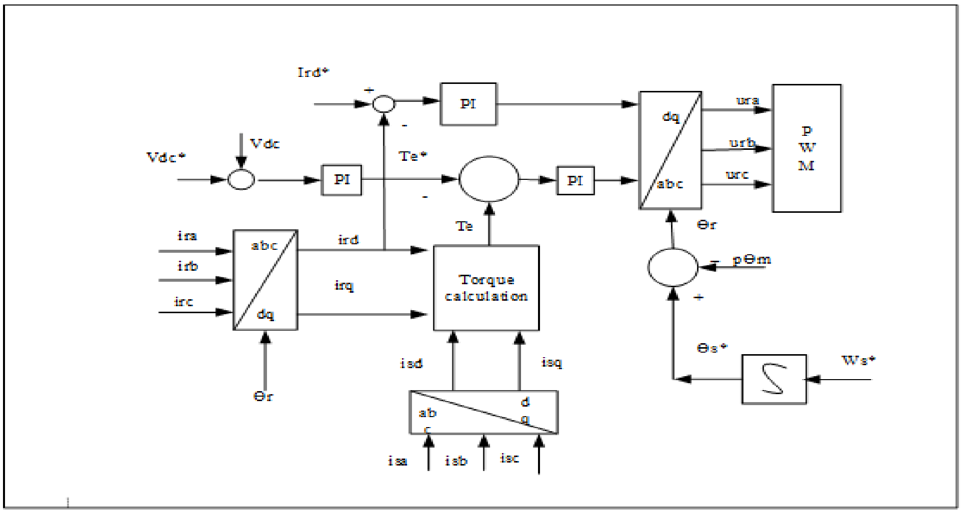

Fig .4: Direct torque and current control with fuzzy logic

Table 2: Comparing the suggested DFIG-DC system with the conventional DFIG-DC system[38]

Property	Standard standalone DFIG	Standard standalone DFIG-DC system	Proposed standalone DFIG system
Power generation type	AC generation	DC generation	AC generation
Control	The rotor is controlled	The rotor is controlled	Both the Rotor and Stator sides are controlled
Number of VSCs used	Two	One	Two
Number of diode rectifiers used	NIL	One (rating equal to stator KVA)	NIL
Equation for modeling	Reference is stator flux	Stator flux is a reference	Reference is Rotor flux
Voltage and frequency on the stator side	fixed	Fixed but oscillatory sometimes due to diode rectifier	Fixed
Voltage and frequency on the rotor side	Changes when slip change	Changes when slip change	Changes with slip
Ripples in torque	Smooth	Ripples	Torque has ripples
Level of voltage	Higher	Lower	Higher
Utilization of kVA ratings of traditional SRIM	KVA ratings on the stator and rotor sides are not used effectively.	KVA ratings on the stator and rotor sides are not used effectively.	Better utilization of both sides.
Harmonics	Switching order	Alternating and using low-order	Alternating and using low-order

4. Results and discussion

The Standalone DFIG is designed and performed in MATLAB/Simulink, as shown in Figure 2. The rating of the system is given in Table 3. The following results are obtained from the proposed controllers implemented in the system in the MATLAB/Simulink environment.

Table 3: Doubly fed induction generator specifications

Type	SRIM
P	1500 W
V_{rms}	380 V
F	50 Hz
V_{rotor}/V_{stator}	1
R_r	2.3 Ω
L_s	4 mH
R_r	3.1 Ω
L_r	2 mH

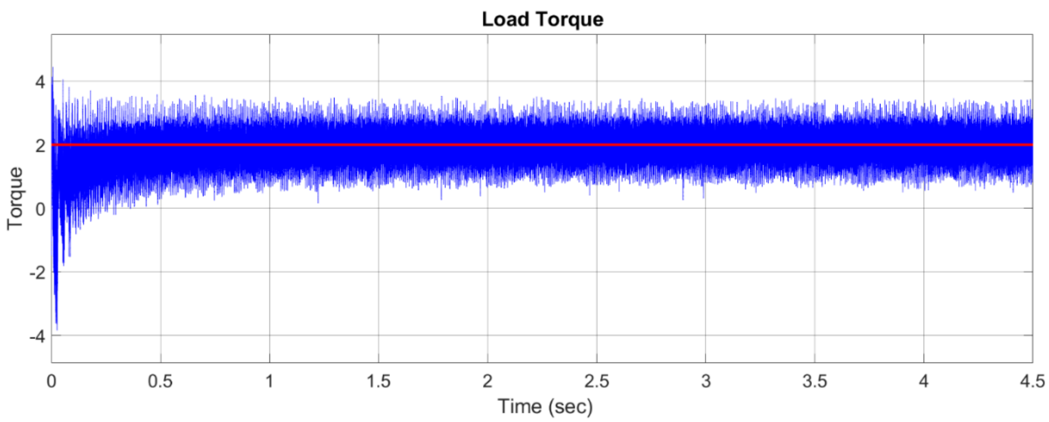

Fig. 5: Waveform of electromagnetic torque for MPC-based DFIG

In Figure 5, the electromagnetic torque is shown for the MPC-based standalone DFIG system. Introduction to the Model predictive current controller in the stator side and rotor side voltage control will significantly reduce the torque ripples and provide the dual side control of the system. The electromagnetic torque is tracking the load torque with some ripples.

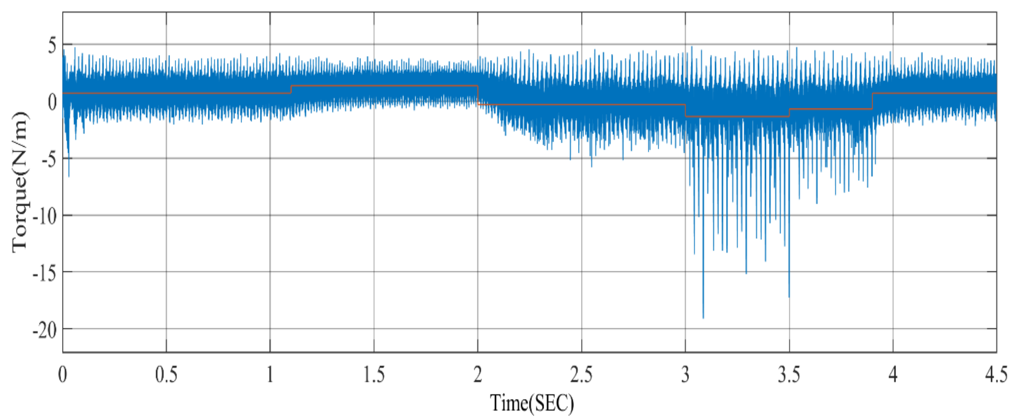

Fig. 6: Waveform of varying electromagnetic torque for MPC-based DFIG

Figure 6 shows electromagnetic torque for the MPC-based standalone DFIG system. The varying electromagnetic torque tracks the load torque with some ripples.

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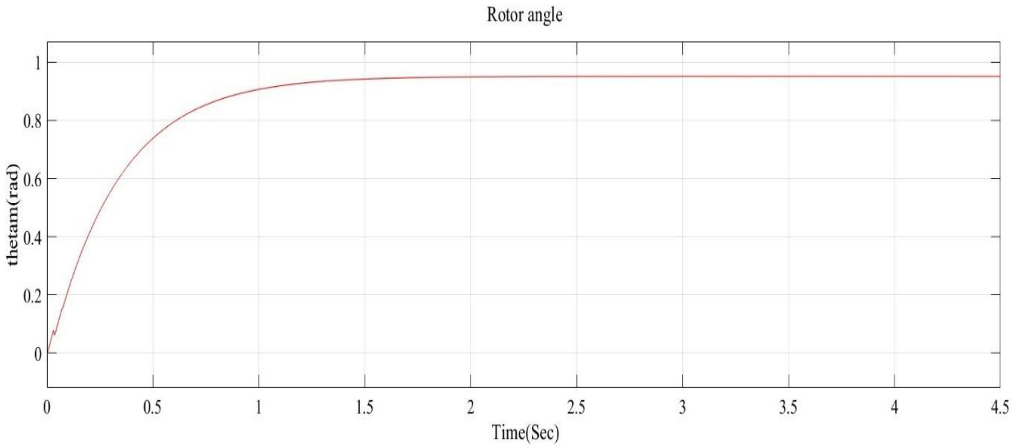

Fig. 7: Waveform of Rotor angle for MPC-based DFIG system

In Fig 7 the Rotor angle is shown and it is found that its value is increasing with time and is getting constant at 1 sec. The magnitude of the rotor angle is around 0.9. This value of the rotor angle is used for the implementation of voltage control and is multiplied by the pole and taken as a reference for the angle.

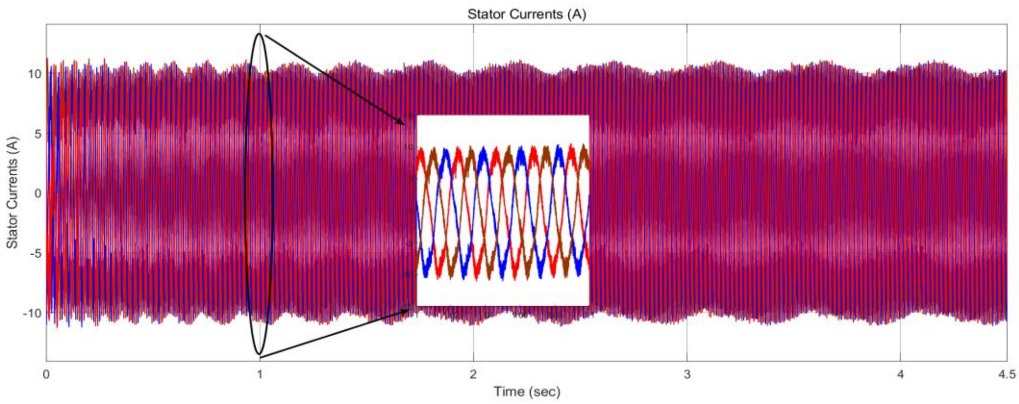

Fig. 8: Waveform of Stator current for MPC-based DFIG system

The waveform of the stator current for the proposed system is shown in Figure8. The nature of the current is sinusoidal in nature and it is sinusoidal throughout the entire running time. Here the result of the current obtained is good and satisfactory. The values of the stator currents are approximately 10A.

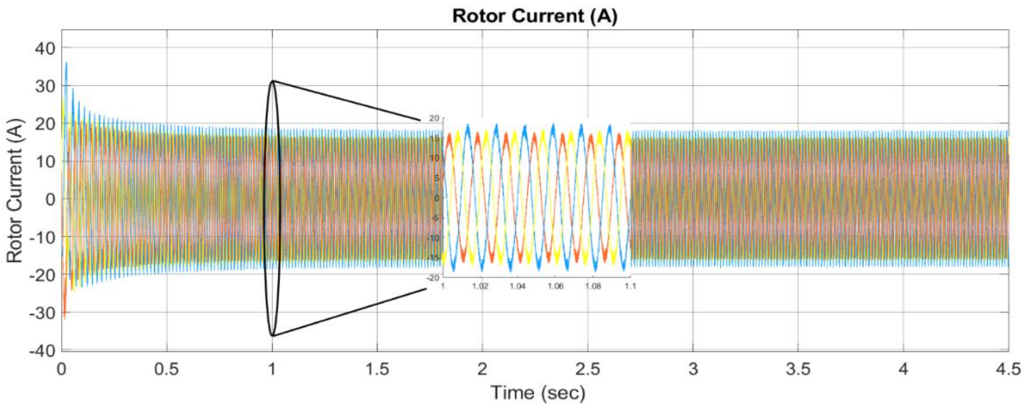

Fig. 9: Waveform of rotor current for MPC-based DFIG system

The Figure9, the waveform of the rotor current for the proposed control system is shown. The value of the rotor current is 20 A for the prescribed system. The time taken is 0.3 sec to reach the steady state. The nature of current is sinusoidal which is a good and sufficient condition for the system.

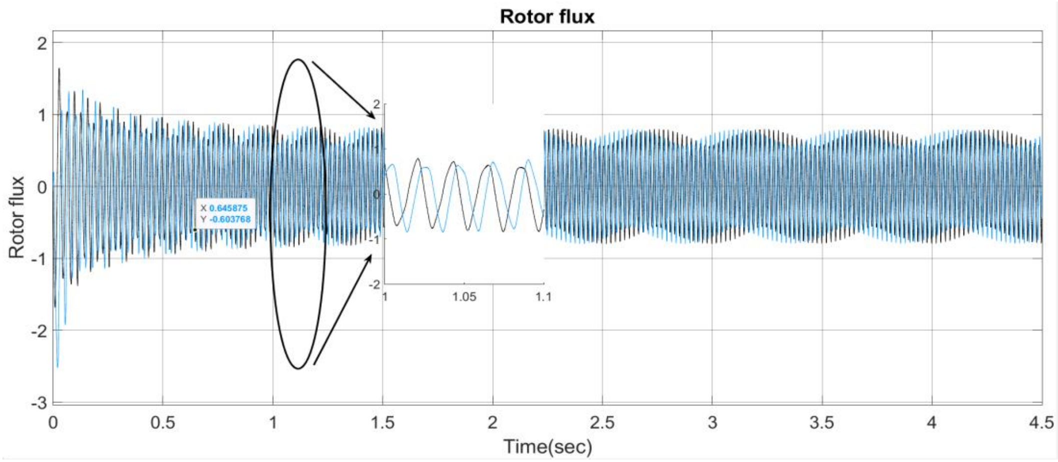

Fig. 10: Waveform of rotor flux in terms of dq- components

The waveform of rotor flux for the MPC-based DFIG system is shown in Figure10. The rotor flux reached to steady state at time, t= 0.5sec. The nature rotor flux is sinusoidal in nature with an amplitude of around 1 which is a necessary and sufficient condition for a reliable system. For estimating the cost function of the MPC controller block the rotor flux plays a significant role.

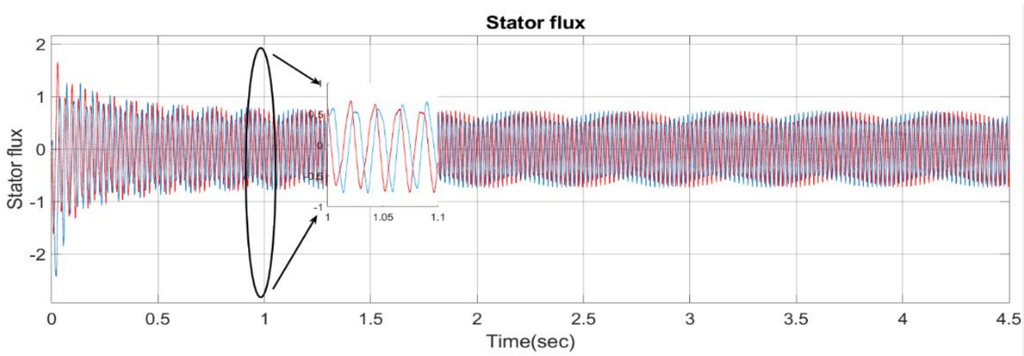

Fig. 11: Waveform of stator flux in terms of dq- components

The waveform of stator flux for the MPC-based DFIG system is shown in Figure 11. The stator flux reached to steady state at time, t= 0.5sec. The nature rotor flux is sinusoidal in nature which is a necessary and sufficient condition for a reliable system.

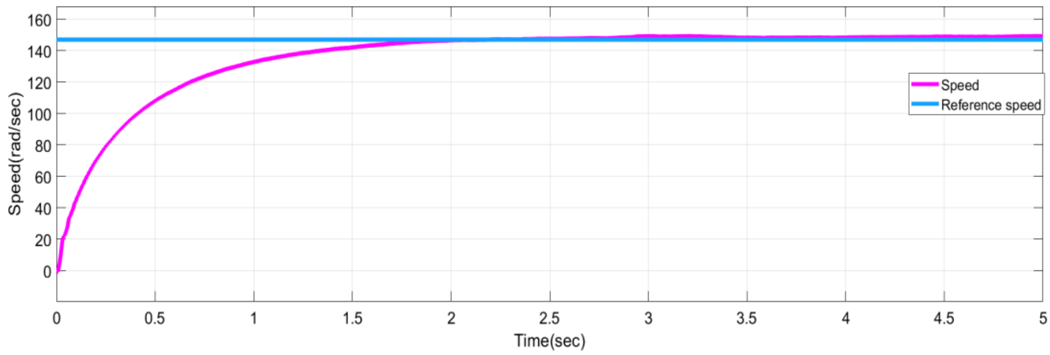

Fig. 12: Speed waveform of DFIG.

Figure 12 shows the DFIG speed waveform. The base or rated speed is 147 rad/sec, and the speed obtained for an MPC-based system is approximately 147 rad/sec, which is very close to the reference speed for load torque of 2 N-m. It took about 1.5 seconds to reach the steady state for a given set of parameters.

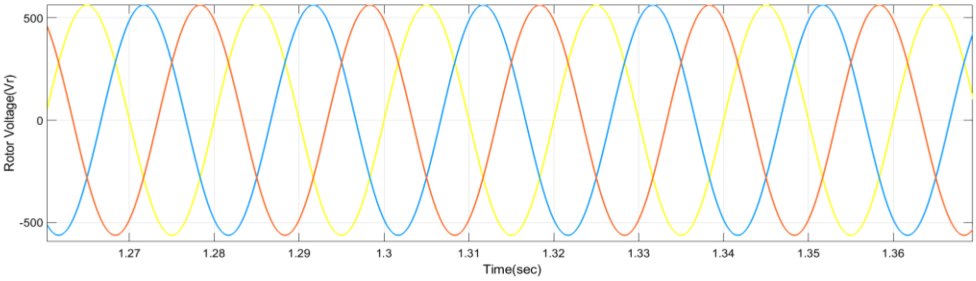

Fig. 13: Rotor voltages of the Standalone DFIG machines

In Figure 13, the rotor voltages obtained are purely sinusoidal and the value of voltage is about 500 V without any grid connection and in standalone mode. The MPC controller will provide ripple free waveform

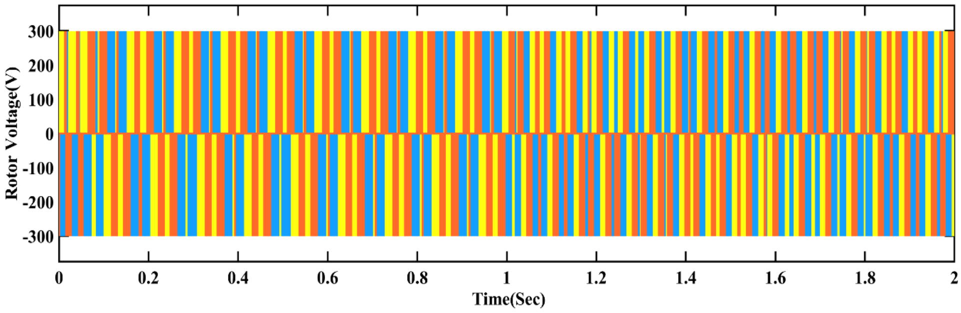

Fig. 14: Rotor voltages of the Standalone DFIG machines

In Figure 14, the rotor voltages obtained are of rectangular pulses with direct current and torque control implemented in the rotor side of DFIG with fuzzy logic and when the stator is not controlled and the value of voltage is 300 V and the time duration is 2 seconds.

In Figure 15, the rotor currents obtained and are purely sinusoidal with very less ripples and amplitude of 20 amperes. Fig 16 shows the stator current with 40 amperes and purely sinusoidal.

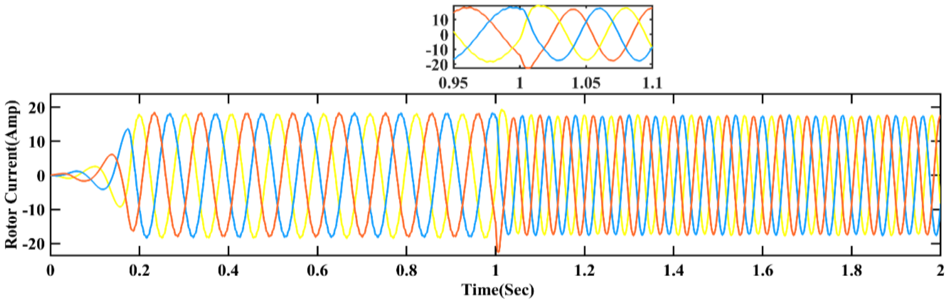

Fig. 15: Rotor currents with direct torque and current control with fuzzy logic in Standalone DFIG machines

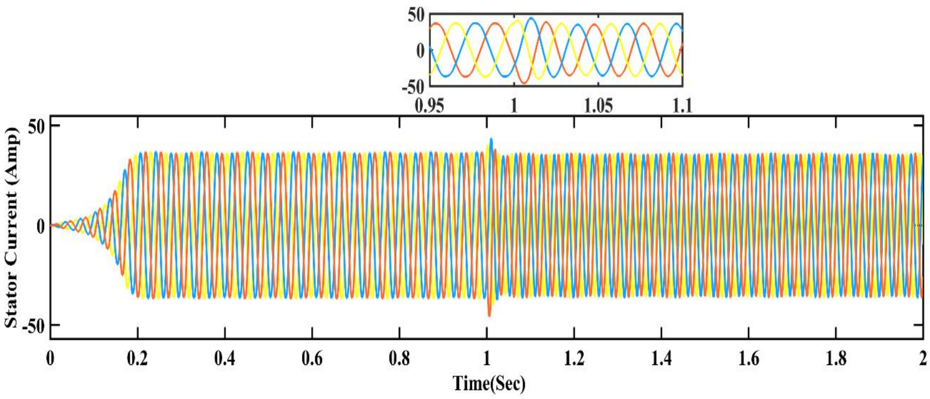

Fig. 16: Rotor currents with direct torque and current control with fuzzy logic in Standalone DFIG machines

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5. Conclusion

Standalone DFIGs with a DC system have a number of benefits as compared to other generators. For instance, the DC system can offer standby electricity in the event of grid outages, which is crucial for remote locations, islands, and ships. By minimizing losses during the AC-DC-AC conversion process and allowing the integration of various renewable energy sources, the DC system can also increase the stability and efficiency of the entire system. Separate DFIGs with a DC system do, however, face some difficulties. To ensure that it can offer adequate energy storage and withstand cycling and charging/discharging operations, for instance, the DC battery bank must be correctly sized and maintained. The power converters must also be meticulously planned and managed to reduce losses and guarantee the stability of the entire system. To overcome these difficulties and improve the performance of standalone DFIGs with a DC system, model predictive and Direct voltage control is proposed. It is found that the output torque is been followed by the given input torque which is a constant value of 2 and if the input torque is varied and not constant then the output torque is varied in the same way and following it with some ripples. The output speed is approaching the reference speed in the standalone mode which is of 147rad/sec and when the direct torque and current control are applied with the fuzzy logic the currents are becoming purely sinusoidal. To verify the aforementioned objectives, the system is performed in MATLAB/Simulink environment.

Nomenclature

ψ_s	stator flux
ψ_r	Rotor flux
T_e	Electromagnetic torque
p	Pole pairs
L_m	Magnetizing inductance
L_r	Rotor inductance
L_s	Stator inductance
σ	Leakage coefficient
C_{dc}	Dc bus capacity
i_L	Load current
v_s , v_r	Rotor and Stator voltage
v_{dc}	DC voltage
R_r , R_s	Rotor and Stator resistance
i_s^*	Reference of stator current
P, Q	Active and Reactive Power
C1	Capacitor
Ura, Urb, Urc	rotor phase a,b,c voltages

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