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International Journal of
Electrical and Electronics Research (IJEER)
Research Article | Volume 10, Issue 2 | Pages 282-289 | e-ISSN: 2347-470X

PMSG Wind Turbine Based Current Fed Three Phase Inverter with Model Predictive Control

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ABSTRACT- Design of an improved Permanent Magnet Synchronous Generator (PMSG) wind turbine power based Current Fed Inverter (CFI) using Model Predictive Controller (MPC) is proposed in this paper. Optimum torque control is proposed in wind energy conversion system, MPC is used to adjust the dynamic response time based on the application need. This model deals with torque control strategy of PMSG in the machine side controller. Impact of normal mode of operation by the copper losses and torque ripples are minimized by maximizing the average torque. Synthetization of adequate stator phase current are obtained naturally. Uncertainty of the steady state errors of the plant and parameter error are rectified in the system model. The designed CFI with MPC was implemented using medium range wind turbine in MATLAB /Simulink. The simulation output shows the better efficiency in over modulation region by the proposed CFI with controller. Constant switching frequency is maintained and efficient required dynamic response (DR) value is attained.

Keywords: PMSG, Wind Turbine, Current Fed Inverter, Model predictive control, over modulation, dynamic response time.

ARTICLE INFORMATION
Author(s): Vijayaprabhu. A and Kumaresan. M
Received: 03/04/2022; **Accepted**: 14/06/2022; **Published**: 28/06/2022;
e-ISSN: 2347-470X;
Paper Id: IJEER220304;
Citation: 10.37391/IJEER.100238
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-10/ijeer-100238.html

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1. INTRODUCTION

Permanent Magnet Synchronous Generator (PMSG) are commonly utilized in the industrial areas for harvesting the extent energy from the sea waves and wind energy. Since it operates at higher production efficiency, a consecutive converter is used to separate it from the grid. It is also completely controllable [1]. Different types of controllers have been used by the developers to control PMSG for attaining the maximum energy. Vector control (VC) and Field-oriented (FOC) techniques with PI controllers are still under the key control methods list for PMSG. This is due to the low current Total Harmonic Distortion (THD), constant switching frequency, zero error condition in steady-state and robustness to varying parameters [2]. Irrespective of its efficiency, it features a significantly slow dynamic response which makes the use of a modulation stage a key factor to resolve this. Direct Virtual Torque Control (DVTC) or Direct Power Control (DPC) based on look up tables and hysteresis controllers are some of the other controllers to control PMSG [3]. These controllers are more robust to parameter variations and achieves peak dynamic response time.

Rapid growth in digitalization controlling techniques, modern control methods like Intelligent control, sliding model control, MPC are identified to vanquish the hitch of the existing distinguished traditional controllers. Comparison with these intelligent controllers, MPC has better performance and obtain the pinpoint to the researchers in the recent decade. In this type, the system considered is of discrete type and the sampling values are predicted based on the system. These sampling values may be either next sampling instant values or the future instants. Based on these an optimal solution is chosen. There are many controllers based on MPC and some of them are hysteresis based MPC, deadbeat predictive control, continuous control set, trajectory-based and finite control set MPCs.

One of the promising predictive control among the above listed is the FCS-MPC uses the switch states has made it the most promising controllers than others [4], [5]. Error reduction is performed by selecting the appropriate switching by using one voltage vector method to reduce the cost function. This yields a transient fast varying response time [6], [7]. The liability of this method is switching frequency is exceedingly variable and peak rippling current. The appropriate voltage vector reduces the cost function whereas the computations required to choose the appropriate voltage vector results in high computational complexity [8], [9].

Two vector based MPC based on the optimization of duty cycle is proposed in [10], [11]. Among the two vectors, one is active vector and the other vector is zero voltage vector. This strategy of two voltage vectors is improved in [12]–[14] which reduce the ripple current. Two voltage vectors based MPC functions better than one voltage vector FCS-MPC. During low speed, switching frequency is also varying. Here, the deadbeat control is combined with MPC for selecting the predictions which

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control the system [15], [16]. But this control system is found to be very sensitive to variations in parameters. A Model free MPC is proposed [17] which use the current samplings to overcome this issue. Modelling error functions are stored to remove error. Multi-vector strategy is used to minimize the current ripples by the application of numerous vectors in all timing instant [18]–[20]. Four-voltage vector is used is used to achieve constant switching frequency [21], [22]. This lowers the ripples in variables. The negative duration time is worked out and applied in every switching period. But it is a bit difficult in real time applications.

MPC steer the flux and torque directly [23]. Comparing MPC with the FOC with same criteria's MPTC proves its efficiency is greater than FOC irrespective of its higher computational time. In MPC normally it uses single cost function is overcome by multi cost function optimization with a ranking system[24]. When it is applied with an asynchronous motor, a appreciable enactment of the system is achieved in a steady state and dynamic behaviour is also achieved without any offline optimization. A multi-objective decision system based on fuzzy logic replaces the weighing factors to improve the THD of the stator current which gives the possible control priorities. Various control objectives are achieved at high computational time [25]. The optimization problem is solved by using the multiple objective function using the ranking based technique which results in multi-objective MPC [26]. This avoids the tuning of weighing factors.

The transient impact on the multistep MPC is focused in [27], [28] which analyse its effect on optimization process. Eclectic start-up selects the function of multistep FCS-MPC and sub-optimality is reduced by extending the convex-hull. System models helps in selecting the optimal solution. However these control models are depends on the feedback values and compared with the error signal to the actual values at different operation points.[29], [30]. MPC differ from other controllers due to fast achievable of DR. Merely, in few applications due to the slower response from the mechanical systems requires very slower response time associated with the control system. In real time applications of wind turbine system, the fast response of the MPC system leads to the instability of the system too. In FCS-MPC, the DR time should be configurable based on the need of the application. Torque transients can be efficiently handled by proper tuning of the response time which is adopted by the industries in nature, there are disturbance rejection response and reference tracking are in control system.

2. PROPOSED MULTI-VECTOR MPC FOR PMSG WITH CFI

Some of the factors of synchronous frame of PMSG considered for discussion are stator voltage, electromagnetic torque can be expressed as [31]

$$U_{sd} = R_S I_{sd} + \frac{d}{dt}\lambda_{sd} - \omega_m \lambda_{sq} \quad (1)$$

$$U_{sq} = R_S I_{sq} + \frac{d}{dt}\lambda_{sq} - \omega_m \lambda_{sd} \quad (2)$$

Where u_s - stator voltage

I_s – stator current

R_s - stator resistance

λ_s - stator flux

ω_m – speed of electrical rotor

$$\lambda_{sd} = L_s I_{sd} + \lambda_f$$
$$\lambda_{sq} = L_s I_{sq} \quad (3)$$

Where λ_f - magnetic flux

Ls- Inductance in the stator

The electromagnetic torque can be presented as

$$T_e = 1.5p(\lambda_{sd} I_{sq} - \lambda_{sq} I_{sd}) \quad (4)$$

Where *Te* - electromagnetic torque

p - pole pairs.

Based on the above equations, current slopes can be derived as

$$\frac{d}{dt} I_{sd} = \frac{1}{L_s}(-R_s I_{sd} + \omega_m L_s I_{sq} + U_{sd}) \quad (5)$$

$$\frac{d}{dt} I_{sq} = \frac{1}{L_s}(-R_s I_{sq} - \omega_m L_s I_{sd} - \omega_m \lambda_f + U_{sq}) \quad (6)$$

Stator resistance are small when compared to that of the stator reactance. Hence their effects are neglected. The derivatives of stator current are simplified as follows,

$$\frac{d}{dt} I_{sd} = \frac{1}{Ls}(\omega_m L_s I_{sq} + U_{sd}) \quad (7)$$

$$\frac{d}{dt} I_{sq} = \frac{1}{L_s}(-\omega_m L_s I_{sd} - \omega_m \lambda_f + U_{sq}) \quad (8)$$

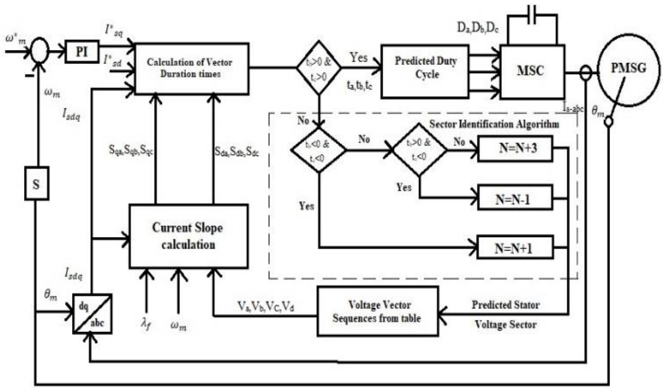

Figure 1: Block representation of proposed MPC with adjustable DR time

2.1 Voltage Vector Sequences

Based on the switch state (V0-V7), eight voltage vectors are produced by the consecutive inverters. Among the eight vectors there are six active vectors, they are V1-V6. The slopes of the eight vectors at any instant can be calculated which is used for the optimization of the duration of voltage vector sequence in any period. There are two zero voltage vectors V0 and V1. At every period, two active voltage vectors will be chosen and converter employs them. Based on the stator voltage sector, selection of vector sequence is chosen as in the following *table 1*.

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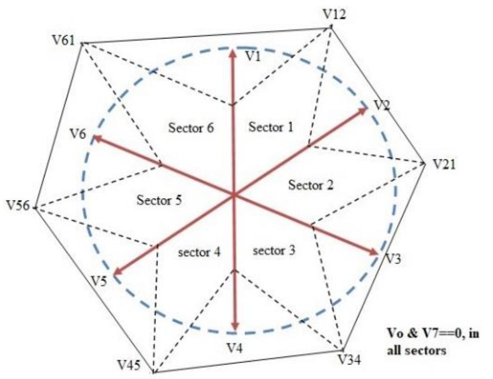

Figure 2: State vector representation of voltage sequence using MPC with adjustable DR time

Table 1: Voltage vector sequence

Vector sequence	Stator voltage sequence (N)					
	1	2	3	4	5	6
Voltage (V_a)	OFF	OFF	OFF	OFF	OFF	OFF
Voltage (V_b)	ON	ON	ON	ON	ON	ON
Voltage (V_c)	ON	ON	ON	ON	ON	ON
Voltage (V_d)	OFF	OFF	OFF	OFF	OFF	OFF

Current Fed Inverter (CFI)

The current fed inverter consists of primary switches *Sa* and *Sb*, six inverter switches *Sc-Sh*, primary diodes Da and Db, output filtering capacitors Cc and Cd, input smoothing inductors *La* and *Lb*, input capacitors *Ca* and *Cb*. Proposed model is shown in *Figure 2*. The CFI operates at four modes.

Mode-1: In this mode of operation by turning on the first primary switch *Sa*, the current passes through and it charges up the inductor La and the current in the inductor increases gradually.

Mode-2: In mode 2 the energy stored in the inductor La from the mode 1 is discharged to the AC loads through the output capacitor by turn OFF the primary switches *Sa* and *Sb*.

Mode-3: In this third mode by applying the switching frequency at the Switch Sb, The current flows through the inductor Lb and charges gradually.

Mode-4: In this fourth mode by applying the shoot through concept by turning ON both the primary switches *Sa* and *Sb*, It charges both the inductors *La* and *Lb* simultaneously and current increases gradually.

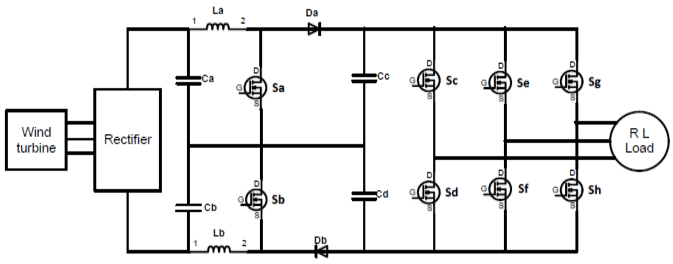

Figure 3: Wind energy based current fed inverter with RL load

The wind energy resource is utilized by the proposed system. The availability of wind power is common everywhere and is utilized for conversion due to its eco-friendly nature and solidity. The received power is handled by the current fed inverter and transfer the rated power to the AC loads. MPC controller is proposed for operating the switches in the CFI by the use of SPWM techniques. The proposed structure is shown in below blocks as *figure 3*.

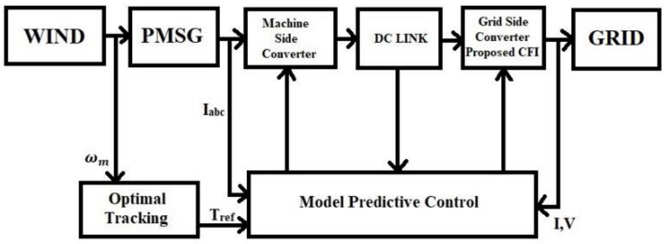

Figure 4: Block diagram of PMSG with CFI under MPC system

3. CONVENTIONAL COST FUNCTION

Desired cost function achieves fast DR with the elimination of tracking error. Elimination of steady state error is achieved by the PI controller at the feedback by generating the corrective function at each instant K along with the cost function, it follows forward-Euler method and produces the stator current equation as,

$$A(K) = K_p.\left(I_{sd}(K) - I^*{}_{sd}(K)\right) + \left(K_i.T_s - K_p\right).\left(I_{sd}(k-1) - I^*{}_{sd}(K-1)\right) + A(K-1) \quad (9)$$

$$B(K) = K_p.\left(I_{sq}(K) - I^*{}_{sq}(K)\right) + \left(K_i.T_s - K_p\right).\left(I_{sq}(k-1) - I^*{}_{sq}(K-1)\right) + B(K-1) \quad (10)$$

Where A(k) - d axis PI output

B(k) - q axis PI output.

The output values are derived at the period of k sampling.

A(k-1) –Previous switching instant of PI controller

B(k-1) Early-stage PI switching instant output.

Kp – proportional coefficients of PI controller

Ki – PI integral gain

Ts – Switching Period.

The above equation can also be drafted as,

$$A(K) = K_p.\left(I_{sd}(K) - I^*{}_{sd}(K)\right) + K_i.T_s\left(\sum_{n=1}^{k-1} I_{sd}(n) - I^*{}_{sd}(n)\right) \quad (11)$$

$$B(K) = K_p.\left(I_{sq}(K) - I^*{}_{sq}(K)\right) + K_i.T_s\left(\sum_{n=1}^{k-1} I_{sq}(n) - I^*{}_{sq}(n)\right) \quad (12)$$

The Cost function can be given as,

$$J_{proposed}(K+1) = |(A(K) + S_{da}t_a + S_{db}t_b + S_{dc}t_c + S_{dd}t_d| + |B(K) + S_{qa}t_a + S_{qb}t_b + S_{qc}t_c + S_{qd}t_d|$$

In the cost calculation function, tracking of stator currents at the current and early instant period K are evaluated.

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Dynamic Response Time

The proportional gain controls the DR time, and it is derives in the second order system using MPC in closed transfer function as,

$$\frac{I_{sd}(Z)}{I^{*}{}_{sd}(Z)} = \frac{I_{sq}(z)}{I^{*}{}_{sq}(Z)} = \frac{K_p(z-1+\frac{R_S T_S}{L_S})}{(Z-1+\frac{R_S T_S}{L_S})(z-1+K_p)} = \frac{K_p}{(Z-1+K_P)} \qquad (13)$$

To reach the maximum steady state of 98.2% at the rise time t_{rise} with the step change, then K_p has to be considered as follows,

$$K_p = 4.(\frac{T_s}{t_{rise}}) \qquad (14)$$

Figure 4 represents the DR time for a unit step for various t_{rise} values. The sampling time is 100µs. For the selected t_{rise} value 98.2% of response time is achieved. Proper choosing of K_p and Ki values achieves the desired DR. Zero steady state error is attained by choosing the one by fourth the switching instant.

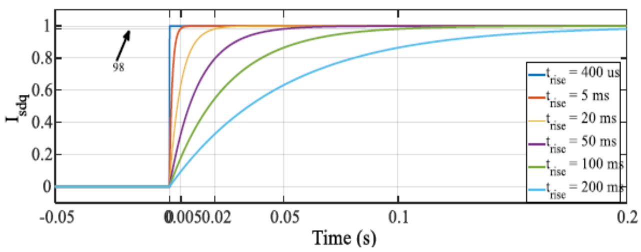


Figure 5: step response for various t_{rise}

Over Modulation

The over modulation region starts at the end of the region of the linear behaviour of the modulation. The region of over modulation continues until there is a complete loss of control. The over modulation index can be represented as follows,

$$M = \frac{\sqrt{U^2{}_{sd}+U^2{}_{sd}}}{V_{dc}} \qquad (15)$$

Where,
M – Modulation index
V_{dc} – DC link voltage

Over modulation occurs at the region when the modulation is more than 1, the percentage of 0.103 higher variation are identified still in the over modulation region it follows the current references by low low frequency harmon is in the stator current. These parameters are considered whie designing the wind turbine which operates at high modulation index can freely cross the over modulation region. Also it can return back to its linear without any loss in its control function.

In this Proposed MPC, the duration time is minimum compared to the switching period, which prolong the calculated times are positive. Hence the normalized duration time as follows,

$$t'_b = \frac{t_b}{t_b+t_c} T_s \,,$$

$$t'_c = \frac{t_c}{t_b+t_c} T_s \,, \qquad (16)$$

$$t'_d = t'_a = 0$$

4. SIMULATION RESULTS AND DISCUSSION

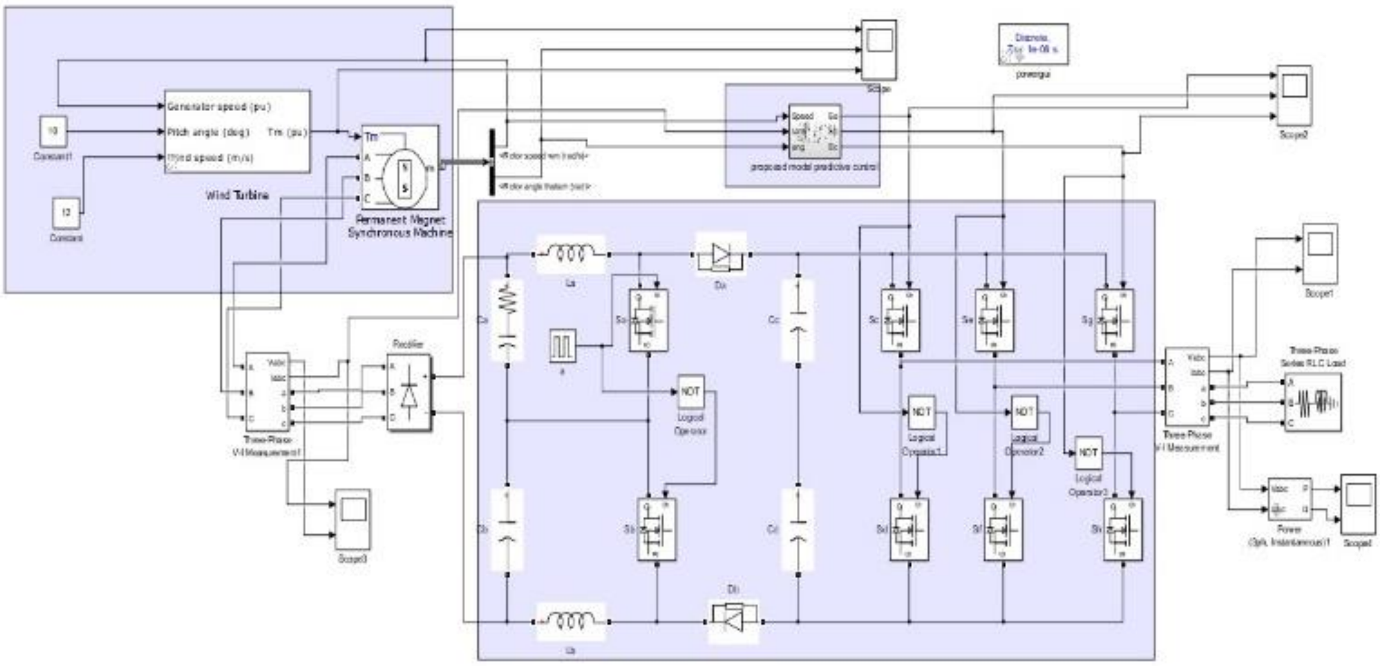


Figure 6: Proposed MPC circuit design

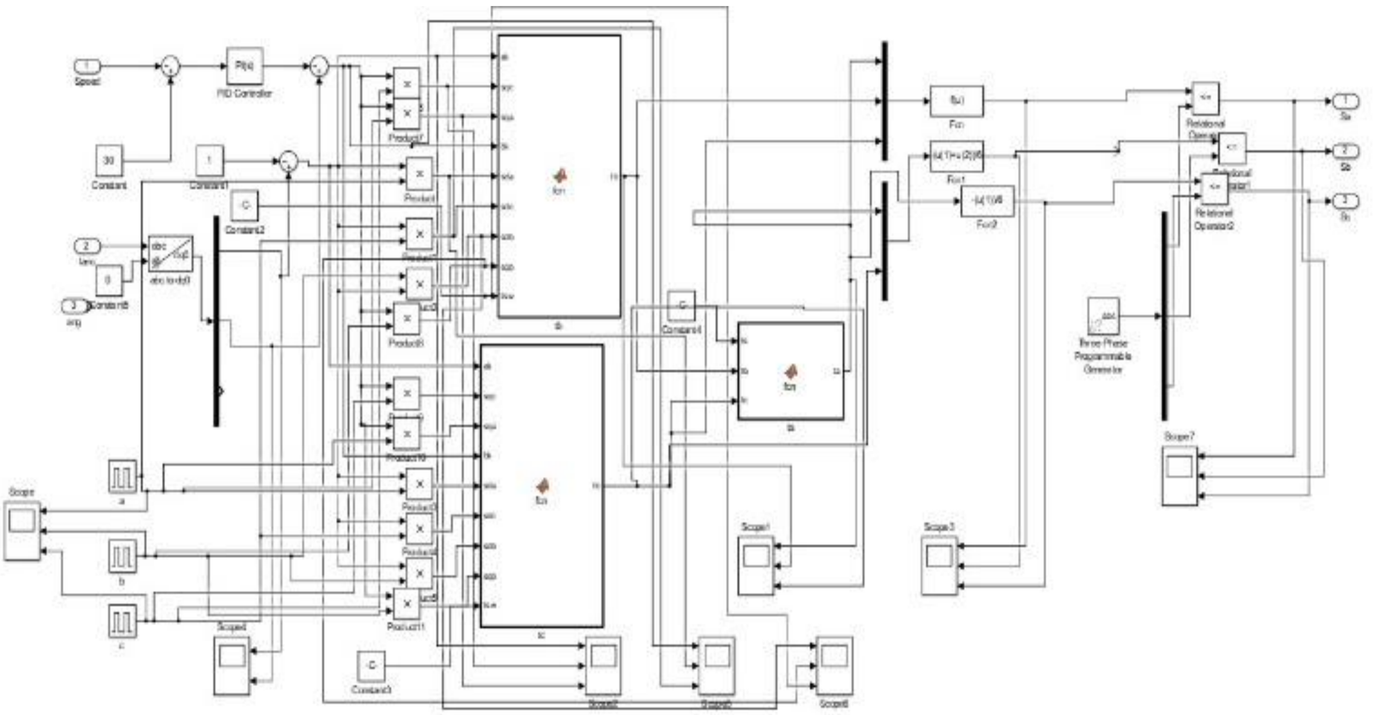
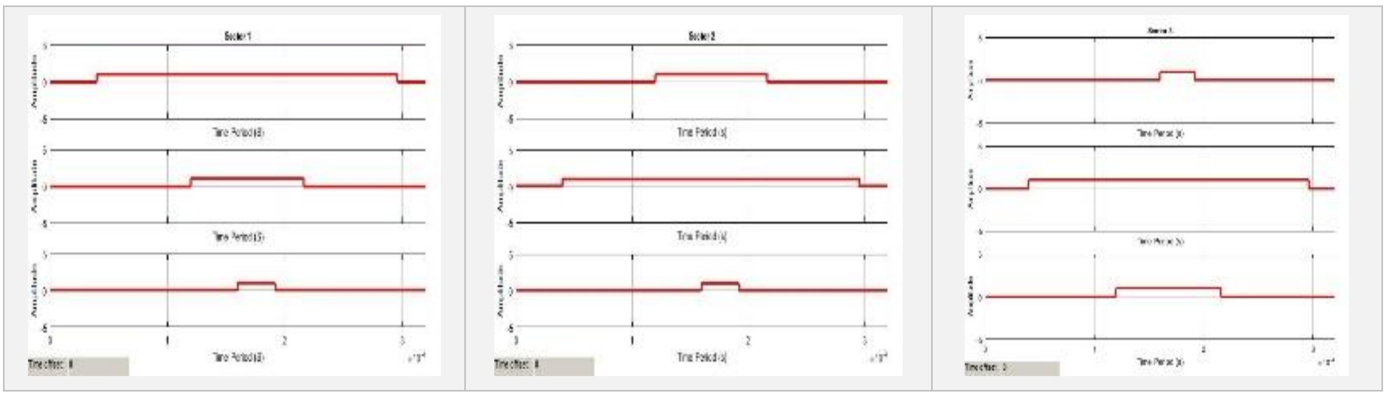


Figure 7: Proposed Model predictive controller design

SECTOR 1 **SECTOR 2** **SECTOR 3**



SECTOR 4 **SECTOR 5** **SECTOR 6**

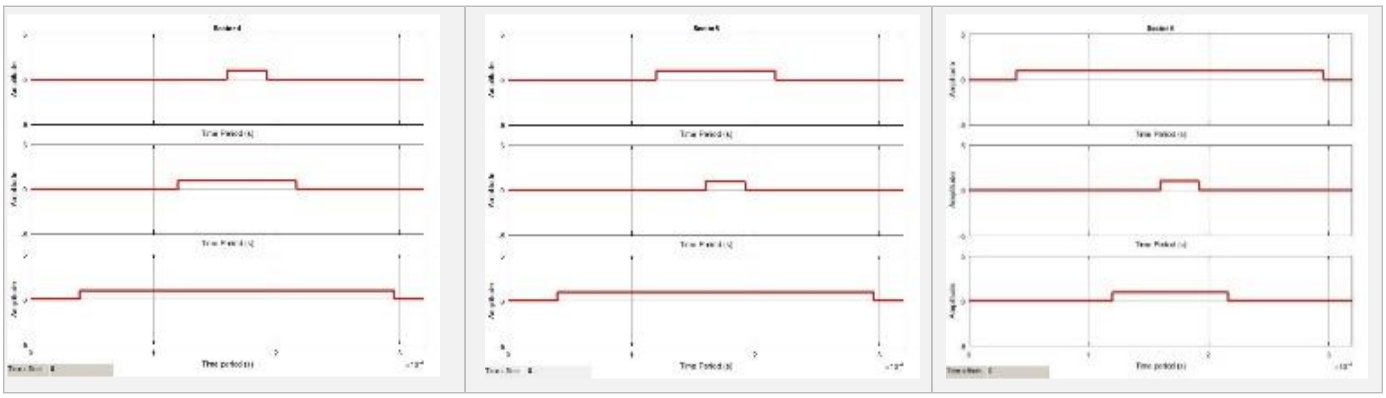


Figure 8: Vector switching sequences Produced to the switches (Da, Db, Dc) in the CFI using MPC

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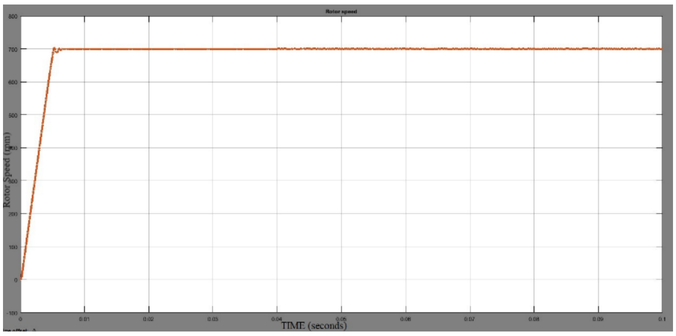

Figure 9: Rotor Speed (rpm)

Over modulation Test

Comparison of conventional MPC with the four-voltage vector MPC is compared. At the test time, the rotor speed is 0.9PU.

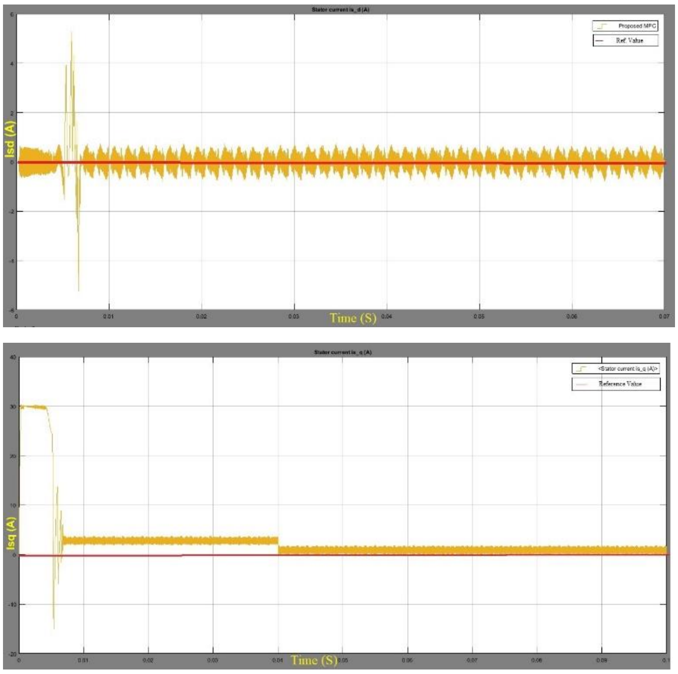

Figure 10: Over modulation region performance of four vector voltage MPC

The robustness of the conventional and the considered MPC methods are compared over a 50% error in the inductance was considered. The current ripple is more in conventional MPC than the considered MPC method. Distortion current is also greater in conventional MPC than the considered MPC. It is observed that with the increase on the errors in the parameters, the steady state error also increases in traditional MPC.

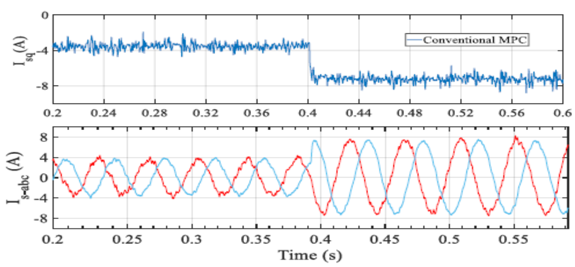

Figure 11: Efficiency of the traditional MPC during 50% inductance error

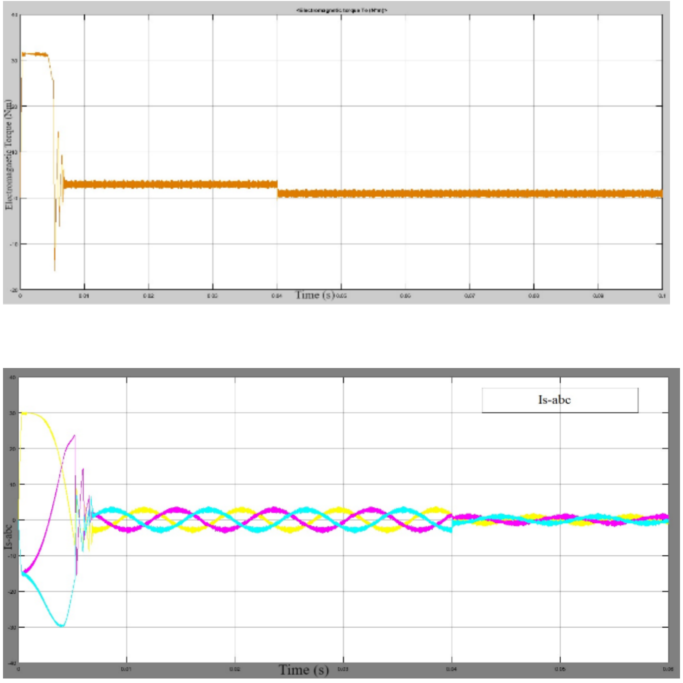

Figure 12: Efficiency of the traditional MPC during 50% inductance error

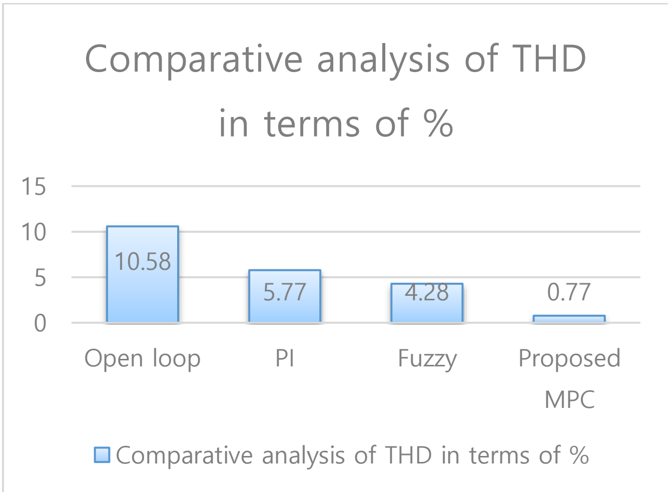

Figure 13: Comparison chart of THD from various controllers in %

5. CONCLUSION

The proposed MPC using CFI proposes four vector approach that generates fixed frequency for switches which attains proper fine-tuning the DR time that balances the working in over-modulation area. These features the compensation of the system in such a case that an application prerequisite slower dynamic directed by the speed of the mechanical system or voltage sag occur in the DC bus. Moreover, proposed MPC using CFI compared with the conventional MPC methods, achieves the zero steady state error with an incorrect parameter of machine, to attain these features Proportional-integral is added to the proposed MPC. Thus, the CFI with wind energy system with MPC system is analysed and simulated. The maximum power is derived through MPC based controller. This MPC based controller system reduces the current ripples. Dynamic response time is greatly increased. Errors are reduced in fast dynamic switching periods. The efficiency of the proposed MPC controller is increased 10% compared to the conventional controller and achieves a total harmonic distortion of 0.66% for fundamental frequency of 50hz. The proposed method shows the successful operation of the system in the over modulation region, in future expansion of this research by changing the controller such as artificial intelligence techniques the overall THD can be further reduced and overmodulation rate can be minimized.

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