Performance Improvement of PCC and PTC Methods of Model-Based Predictive Direct Control Strategies for Electrical Drives using PMSM with Multilevel Inverter

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Received: 6 December 2017 Accepted: 31 December 2017 Published: 15 January 2018

Abstract

In Power Electronics, Predictive Current control (PCC) and Predictive Torque control (PTC) methods are advanced control strategy. To control a Permanent Magnet Synchronous motor machine (PMSM) or induction machine (IM), the predictive torque control (PTC) method evaluates the stator flux and electromagnetic torque in the cost function and Predictive Current control (PCC) [1] considers the errors between the current reference and the measured current in the cost function. The switching vector selected for the use in IGBTs minimizes the error between the references and the predicted values. The system constraints can be easily included [4, 5]. The weighting factor is not necessary. Both the PTC and PCC methods are most useful direct control methods with PMSM method gives 10

Index terms— electrical drives, predictive current control (PCC), predictive torque control (PTC), permanent magnet synchronous motor (PMSM), induction motor, 15-l

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Abstract-In Power Electronics, Predictive Current control (PCC) and Predictive Torque control (PTC) methods are advanced control strategy. To control a Permanent Magnet Synchronous motor machine (PMSM) or induction machine (IM), the predictive torque control (PTC) method evaluates the stator flux and electromagnetic torque in the cost function and Predictive Current control (PCC) [1] considers the errors between the current reference and the measured current in the cost function. The switching vector selected for the use in IGBTs minimizes the error between the references and the predicted values. The system constraints can be easily included [4,5]. The weighting factor is not necessary. Both the PTC and PCC methods are most useful direct control methods with PMSM method gives 10% to 30% more torque than an induction motor also not require modulator [3]. Induction motor work on only lagging power factor means it can produce only 70-90% of torque produced by PMSM with same current. PCC and PTC method with 15-level H-bridge multilevel inverter using PMSM reduces 23% more THD in torque, speed and stator current compared to PCC and PTC method with 15level H-bridge multilevel inverter using induction motor [21].

Switching losses are minimized because the transistors are only switched when it is needed to keep torque and flux within their bounds. The switching pattern of semiconductor switches used to get better performance of multilevel inverter. In this paper, the PTC and PCC methods with 15-level H-bridge multilevel inverter using PMSM and IM are carried out; gives excellent torque and flux responses, robust, and stable operation achieved compared to the PTC and PCC methods with 2-level voltage source inverter. This novel method attracted the researchers very quickly due to its straightforward algorithm and good performances both in steady and transient states [8].

1 INTRODUCTION

urrent control (PCC) and Predictive Torque control (PTC) methods are promising methods. Along reducing torque ripples, the FCS-PTC method also illustrates a number of advantages, like the easy inclusion of constraints, easy implementation, straightforward, algorithm and fast dynamic responses.

The basic concept of model predictive direct torque control (MPDTC) method is to calculate the required control signals in advance [6]. In the MPDTC method, pulse width modulation is needless. The inverter model is required in the control method. During MPDTC, the PTC and PCC method calculates all possible voltage vectors within one sampling interval and selects the best one by using an optimization cost function [7]. To date, the PCC and PTC methods have been adapted in many operational situations and widely investigated, as given in the articles [8], [9]. Now a day, if a semiconductor switch is directly connected to the system with Medium sized voltage grids will create problems. To solve this problem, a multilevel inverter topology has been introduced as an alternative solution for medium voltage and high voltage and extra high voltage power situations. A multilevel inverter can be used renewable energy as a source and can achieve high power rating. So, solar, fuel cells and wind like renewable energy sources can be easily interfaced to a multilevel inverter structure for a high power application. The multilevel inverter concept has been used for past three decades. Multilevel inverter (MLI) has become more popular over the year and magnetized considerable affection in recent years. The MLI generating a stepped voltage waveform which has compressed the harmonic distortion because of inclusion a group of power semiconductor devices and capacitor as voltage sources. The number of merits of MLI is its ability to reduce voltage stress on power switches, dv/dt ratio and common mode voltage, thus improving the quality of the output [1]. There are various topologies of MLI such as Diode Clamped Multilevel Inverter, Cascaded Multilevel Inverter and Flying Capacitor Multilevel Inverter. Out of which H-Bridge multilevel inverter has various advantages such as generate output voltages with extremely low distortion, and lower and draw input current with very low distortion, generate smaller common-mode (CM) voltage, thus reducing the stress on the motor bearings and can operate with a lower switching frequency.

In this paper, the PTC and PCC methods with 15-level H-bridge multilevel inverter using PMSM and IM are carried out by simulation method and compared with the PTC and PCC methods with 2-level voltage source inverter. PCC and PTC method with 15-level Hbridge multilevel inverter using PMSM reduces 23% THD in torque, speed and stator current compared to PCC and PTC method with 15-level H-bridge multilevel inverter using an induction motor **??**10] [24]. Switching losses are minimized because the transistors are only switched when it is needed to keep torque and flux within their bounds. This novel method attracted the researchers very quickly due to its straightforward algorithm and good performances both in steady and transient states [8].

2 II.

3 Modeling of PMSM

The mathematical model of a PMSM given by complex equations in the rotor reference frame is as below: Voltage equations are given by:?? ?? = ?? ?? ?? ?? ? ð ??"ð ??" ?? ?? ?? + ???? ?? ???? [1] ?? ?? = ?? ?? ?? ?? ? ð ??"ð ??" ?? ?? ?? + ???? ?? ???? [2]

Flux linkage is given by ?? ?? = ?? ?? ?? ?? [3] ?? ?? = ?? ?? ?? ?? + ?? ð ??"ð ??" [4] Substituting Equation The developed motor torque is being given by?? ?? = 3 2 ? ?? 2 ? ??? ?? ?? ?? ? ?? ?? ?? ?? ? [8] ?? ?? = 3 4 ????? ð ??"ð ??" ?? ?? + ??? ?? ? ?? ?? ??? ?? ?? ?? ? [9]

?? ?? = ?? ?? + ??ð ??"ð ??" ?? + ?? ??ð ??"ð ??" ?? ???? [10] Solving for rotor mechanical speed from equation 10, we get,ð ??"ð ??" ?? = ? ? ?? ?? ??? ?? ???ð ??"ð ??" ?? ?? ? ???? [11]

And rotor electrical speed isð ??"ð ??" ?? = ð ??"ð ??" ?? ? ?? 2 ? [12]

III. Cascaded H-Bridge Multilevel Inverter

The output phase voltage generalized use as?? = ?? ??1 + ?? ??2 + ?? ??3 + ?? ??4 + ?? ??5 ? ? ? + ?? ???? [13]

The Fourier transform of the corresponding stepped waveform follows [9,5]:U(?t) = 4U dc ? ?[cos(n? 1) + cos(n? 2) + ? + cos(n? l)] sin(n?t) n [**14**]

where n = 1,3,5,7.

By choosing conducting angles, ? 1 , ? 2 ,??.,? l , such that the total harmonic distortion (THD) is minimized. Predominately, these conduction angles for suppressing lower frequency harmonics of 5th, 7th, 11th, and 13th,? orders are eliminated in output [10] [24].

4 PREDICTIVE DIRECT CONTROL METHODS FOR PMSM a) Predictive Current Control (PCC)

Predictive Current Control (PCC) uses only the predicted stator currents in the stationary reference frame in order to control the multiphase drive. Current references are obtained in the rotating reference frame from an outer PI speed control loop and a constant ??component current and then mapped in the stationary reference frame in order to be used in the cost function, as shown in Fig. **??**.

5 Fig. 2: Predictive Current Control using MPC

The aim is to generate a desired electric torque, which implies sinusoidal stator current references in ??-??-?? phase coordinates. In the stationary ?-?-??-?? reference frame, the control aim is traduced into a reference stator current vector in the ??-?? plane, which is constant in magnitude, but changing its electrical angle following a circular trajectory, and depending on the implemented multiphase machine, either null or non-null reference stator current vector in the ??-?? plane. The PMSM model, stator current is as below: [15] where?? ?? = ? 1 ?? ?? ???? ?? . ???? ?? ???? ? ?? ?? . ? 1 ?? ?? ? ??. ð ??"ð ??"? . ?? ?? ? ? ?? ?? ??? ?? = ?? ?? ?? ?? , ?? ?? = ?? ?? + ?? ?? 2 . ?? ?? ?????? ?? ?? = ??. ?? ??

The forward Euler discretization is considered to predict the next step value as???? ???? ? ??(??+1)???(??)

?? ?? [16] where T s is the sampling time of the system. Using (**??**5) and (**??**6), the stator current can be predicted as??? ?? (?? + 1) = ?1 ? ?? ?? ?? ?? ? . ?? ?? (??) + ?? ?? ?? ?? . 1 ?? ?? . ??? ?? . ? 1 ?? ?? ? ??. ð ??"ð ??"(??)? . ?? ?? (??) + ?? ?? (??)? [17] ?? ?? = ??. ?? ?? ?? ??

The cost function is represented as below:ð ??"ð ??" ?? = ? ???? ?? * ? ?? ?? (?? + ?) ?? ? + ??? ?? * ? ?? ?? (?? + ?) ?? ?? ?? ?=1 [18]

The corresponding reference values for the field-and torque-producing currents?? ?? * and ?? ?? * are produced by?? ?? * = |?? ?? | * ?? ?? , ?? ?? * = 2 3 ?? ?? ?? ?? ?? * |?? ?? | * [20]

In the cost function, the state's current values in ?? frame are required. The inverse Park transformation is presented to satisfy this requirement as follows:? ?? ?? ? = ? ??????(??) ???????(??) ??????(??) ??????(??) ? ? ?? ?? ? [21] b) Predictive Torque Control (PTC)

Fig. **??**: Predictive Torque Control using MPC Predictive Torque Control (PTC) based on FCS-MPC for three phase two-level induction motor drives given in [20] is shown in Fig. **??**. It is done by an outer PI based speed control and an inner PTC and controlled variables are the stator flux and torque. Torque reference is provided by an external PI, based on the speed error, while the stator flux reference has been set at its nominal value for base speed operation. Then the cost function [10] [24] is evaluated and the switching state with a lower cost (??) is applied to the VSI. In order to improve PTC performance in [17] a modified cost function was presented, aimed to not only control stator flux and produced torque but also limit the maximum achievable ??-?? stator currents to (?????????????) and reducing harmonic components in the ??-?? plane.

The core aspects of PTC are the torque and flux predictions and the design of a cost function. In the predictive algorithm, the next-step stator flux ? ?s(k + 1) and the electromagnetic torque ? T(k + 1) must be calculated. By using (9) to discretize the voltage model (1), the stator flux prediction can be obtained as?? ? ?? (?? + 1) = ?? ?? (??) + ?? ?? . ?? ?? (??) ? ?? ?? . ?? ?? . ?? ?? (??) [22]

The electromagnetic torque can be?? ? (?? + 1) = 3 2 . ??. ????{?? ? ?? (?? + 1) * . ??? ?? (?? + 1)} [23]

The classical cost function for the PTC method isð ??"ð ??" ?? = ? ???? * ? ?? ? (?? + 1) ?? ? + ??. ???? ?? * ? ? ??? ? ?? (?? + ?) ?? ??? ?? ?=1

[24]

V.

6 Results

a) PCC and PTC method with PMSM and IM using 15-level inverter PCC and PTC for a 4-pole induction machine have simulated with 15-level multilevel inverter and compared with 2-level voltage source inverter. The rating of induction motor is 5HP, 440V, 50Hz, 1440 RPM star connected induction motor. For all simulations, the motor characteristics will be utilized as below:

where PCC and PTC for a 4-pole PMSM have simulated with 15-level multilevel inverter and compared with 2-level voltage source inverter. For all simulations, the motor characteristics will be utilized as below: The parameters of PMSM motor are given in Table **??**I. For all simulations, the motor characteristics will be utilized as below: = [0,0, 0,0] Sampling Time (Sec) =1

The Matlab, Simulink model of PCC and PTC methods with PMSM using 15-level inverter shown in fig. **??** and fig. **??**. To achieve a comparison between the two methods, the external PI speed controllers are configured with the same parameters. The results of the PCC method and the PTC method with PMSM using 15-level inverter is shown in fig. 5, fig. **??** compared with the simulation results of the PCC method and the PTC method with IM using 15-level inverter shown in Fig. **??**, Fig.8 [10] [24]. From the pictures, we can see that both methods have good and similar behaviors at this point in the operation. The PCC method has a slightly better current response; however, the torque ripples of the PTC method are lower than those of the PCC method. The performances in the whole speed range are investigated in the simulations. The motor rotates from positive nominal speed to negative nominal speed. During this dynamic process, the measured speed, the torque, and the stator current are observed. It is clear that both methods have very similar waveforms. They each have almost the same settling time to complete this reversal process due to the same external speed PI parameters. The torque ripples of the PTC method are slightly lower than those of the PCC method. From these simulations, we can conclude that two methods can work well in the whole speed range and have good behaviors with the full load at steady states. **??**c) represent the corresponding speed, torque and stator current response of the PTC and PCC schemes with a 15-level inverter using IM. The THD in speed, electromagnetic torque and stator current in the PCC and PTC method with IM using 15-level inverter is shown in Fig. 11(a), (b), (c) and Fig. 12 (a), (b), (c) respectively. It can be compared that, the THD in speed, torque, and stator current with PCC is approximately 5.3% reduces while with PTC is approximately 4.8% reduces in the conventional scheme as per article [10]. In the proposed scheme with 15-level inverter, the THD in speed, torque and stator current with PCC is approximately 23% reduces while, with PTC is approximately also 23 % reduces, which proves the superiority of the proposed PCC and PTC scheme with 15-level inverter over the conventional one compare to article **??**10] [23] [24]shown in Table **??**3.

7 b) PCC and PTC method with PMSM and IM using 2-level inverter

The Matlab, Simulink model of PCC and PTC methods with PMSM using 2-level inverter shown in fig. **??** and fig. **??**. To achieve a comparison between the two methods, the external PI speed controllers are configured with the same parameters. The simulation results of the PCC method and the PTC method with PMSM using 2-level inverter is shown in fig. 13(a),(b),(c) and fig. 14 (a),(b),(c) compared with the simulation results of the PCC method and the PTC method with IM using 2-level inverter shown in Fig. 15 (a),(b),(c), Fig. 16 (a),(b),(c) respectively [10] [24]. The PCC method has a slightly better current response; however, the torque ripples of the PTC method are lower than those of the PCC method. The performances in the whole speed range are investigated in the simulations. The motor rotates from positive nominal speed to negative nominal speed. During this dynamic process, the measured speed, the torque, and the stator current are observed. It is clear that both methods have very similar waveforms. They each have almost the same settling time to complete this reversal process due to the same external speed PI parameters. The torque ripples of the PTC method are slightly lower than those of the PCC method. From these simulations, we can conclude that two methods can work well in the whole speed range and have good behaviors with the full load at steady states.

© Total harmonic distortion (THD) has calculated successfully in this article by using MATLAB 2013. The proposed scheme shows better response as compared to the conventional one in terms of Total Harmonic Distortion (THD) in speed, torque, and stator current during transient conditions. Fig. 13 (a), (b), (c) and Fig. 14 (a), (b), (c) represent the corresponding speed, torque and stator current response of the PTC and PCC schemes using PMSM with a 2-level inverter. The THD in speed, electromagnetic torque and stator current in the PCC and PTC using PMSM with 2-level inverter is shown in Fig. 17(a),(b),(c) and Fig. 18 (a), (b), (c) respectively. Similarly Fig. 15(a), (b), (c) and Fig. 16 (a), (b), (c) represent the corresponding speed, torque and stator current response of the PTC and PCC schemes using IM with a 2-level inverter. The THD in speed, electromagnetic torque and stator current in the PCC and PTC method a 2-level inverter is shown in Fig. 19(a), (b), (c) and Fig. 20 (a), (b), (c) respectively. It can be compared that, the THD in speed, torque, and stator current with PCC is approximately 5.3% reduces while with PTC is approximately 4.8% reduces in the conventional scheme as per article [10] [24]. In the proposed scheme with 2-level inverter, the THD in speed, torque and stator current with PCC is approximately 19% reduces while, with PTC is approximately also 36 % reduces, which proves the superiority of the proposed PCC and PTC scheme with 2-level inverter over the conventional one compare to article [10] [23] shown in Table **??** 2.

Both the PTC and PCC methods are most useful direct control methods with PMSM method gives 10% to 30% more torque than an induction motor also not require modulator [3]. Induction motor work on only lagging power factor means it can produce only 70-90% of torque produced by PMSM with same current. Total harmonic distortion (THD) has calculated successfully in this article by using MATLAB 2013 compare to [10] [24]. The PCC and PTC method with 15-level H-bridge multilevel inverter using PMSM reduces 23% more THD in torque, speed and stator current compared to PCC and PTC method with 15-level H-bridge multilevel inverter using an induction motor shown detail in Table **??**3 [21]. The graphical representation of % THD in rotor speed, electromagnetic torque and stator current also shown in graph-1,2,3. The comparative issues between PCC and PTC also shown in Table

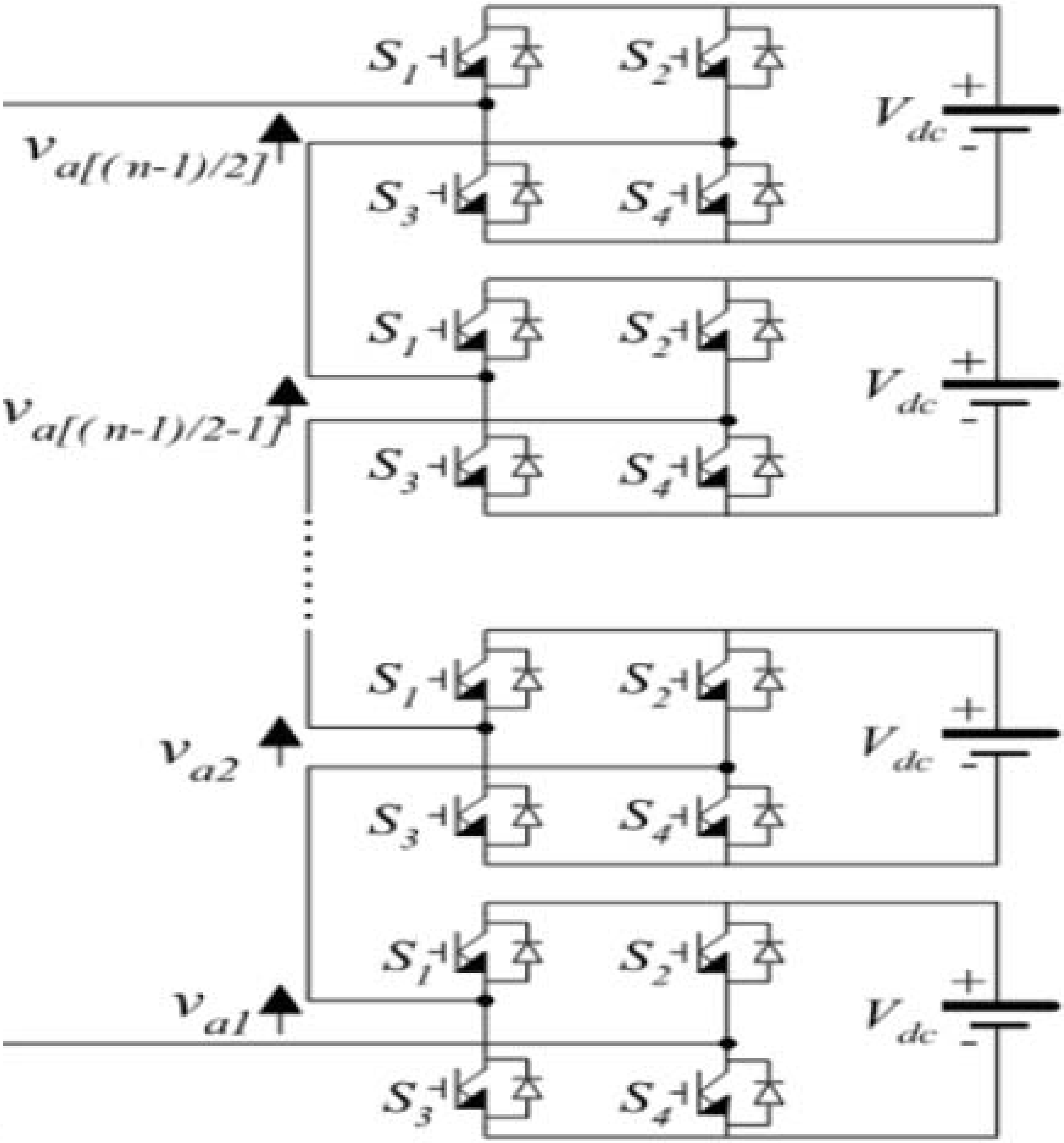
8 c) THD Analysis of PCC and PTC Method

9 CONCLUSION

In this paper, PCC and PTC methods of MPC family with 15-level multilevel inverter have been presented and discussed by simulation method only. PCC and PTC methods with 15-level multilevel inverter are direct control methods without an inner current PI controller or a modulator, the PCC method with 15-level multilevel inverter has lower calculation time than the PTC method with 15-level multilevel inverter, fast dynamic response, and Lower stator current harmonics than PTC. This advantage makes the PCC method more accurate for applications with longer prediction horizons. From the test results, it is clear that the PCC method and the PTC method with 15-level multilevel inverter have very good and similar performances in both steady and transient states. PTC method with 15-level multilevel inverter has lower torque ripples; however, the PCC method with 15-level multilevel inverter is better when the currents are evaluated. This novel method attracted the researchers very quickly due to its straightforward algorithm and good performances both in steady and transient states. Future work is to test switched reluctance motor, and servo motor with multilevel inverter is applied to PCC and PTC method, we can imagine that the PCC algorithm and PCC algorithm will greatly reduce the calculation time.

The PCC method shows strong robustness with respect to the stator resistance; however, the PTC method shows much better robustness with respect to the magnetizing inductance.

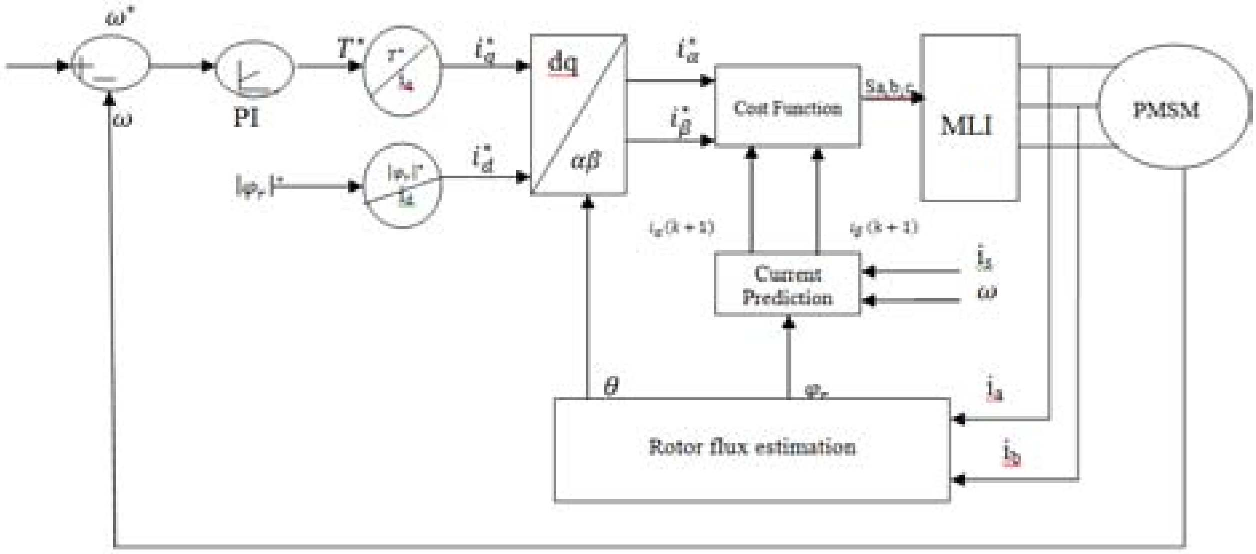
10 Global



1

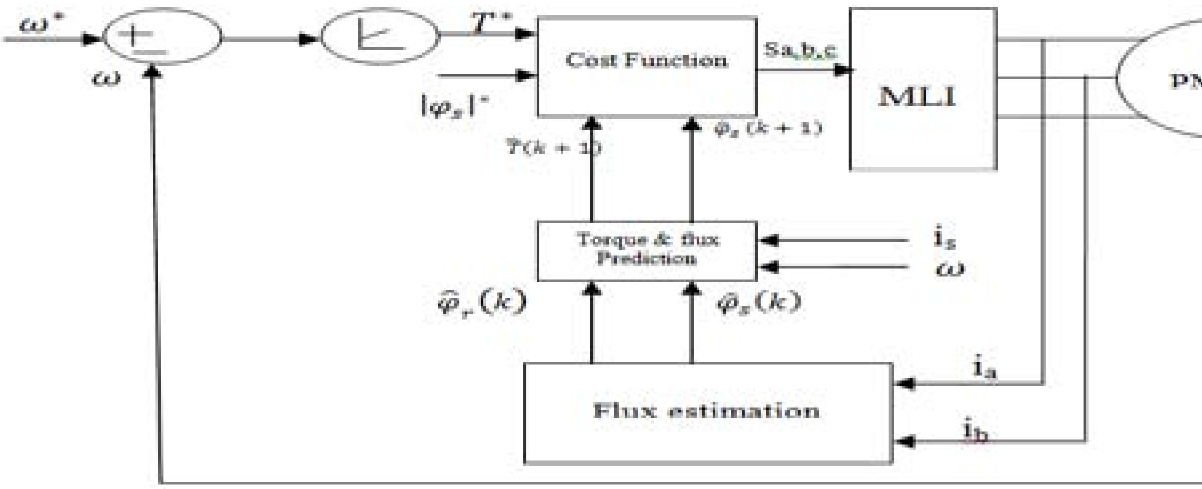
Figure 1: Fig. 1 :

[1]



5

Figure 2: Fig. 5 :



5566667778

Figure 3: Fig. 5 :Fig. 5 :Fig. 6 :Fig. 6 :Fig. 6 :Fig. 6 :Fig. 7 :Fig. 7 :Fig. 7 :Fig. 8 :

?? ???? ??? ?? ?? ?? + ?? ð ??"ð ??" ?

Arranging equation 5 and 6 in matrix form,

? ?? ?? ?? ?? ? ?? ?? + ?ð ??"ð ??" ?? ?? ?? ?? ?? + ???? ?? ???? ð ??"ð ??" ?? ?? ?? ???? ?? ????

=

?

Figure 4:

1

Stator Resistance (ohm)	= 1.403
Rotor Resistance (ohm)	= 1.395
Stator Self Inductance (H)	= 0.005839
Rotor Self Inductance (H)	= 0.005839
Mutual Inductance	(H)= 0.2037
No. of poles	= 4
Moment of Inertia (kg.m^2)	= 0.0005
Sampling time,	= 1 Sec

Figure 5: Table 1 :

2

Stator phase resistance Rs (ohm)	= 4.3
Armature Inductance (H)	= 0.0001
Flux linkage established by magnets (U.s)	= 0.05
Voltage Constant (U_peak L-L / krpm)	= 18.138
Torque Constant (N.m / A_peak)	=0.15
Inertia, friction factor, pole pairs [J (kg.m^2)]	=0.000183
Friction factor F (N.m.s)	= 0.001
Pole pairs p( )	=2
Initial conditions[wm(rad/s) thetam(deg) ia,ib(A)]	

Figure 6: Table 2 :

0.9
thd_rotor_speed_ptc_im2 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
0 0 0.01 0.02 0.03 0.04
Time
thd_electromagnetic_torque_ptc_im2 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 0 0.01 0.02 0.03 0.04 T

thd_stator_current_ptc_im2 0 0.9 0 0.01 0.02 0.03
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Figure 7:

3

Sr. No.	Different Methods	Rotor Speed (w_r)	%THD in Torque (T_e)	Stator Current
1	PCC with PMSM using 15-level multilevel inverter	31.44	31.34	44.85
2	PTC with PMSM using 15-level multilevel inverter	21	21	118
3	PCC with IM using 15-level multilevel inverter	54.24	155.2	53.22
4	PTC with IM using 15-level multilevel inverter	41.51	41.51	89.67
5	PCC with PMSM using 2-level voltage source inverter(VSI)	82.45	68.60	39.39
6	PTC with PMSM using 2-level voltage source inverter(VSI)	106.11	41.40	90.02
7	PCC with IM using 2-level voltage source inverter(VSI)	118.86	98.14	72.21
8	PTC with IM using 2-level voltage source inverter(VSI)	57.20	79.38	102.34
9	Direct Torque control of IM using 2-level voltage source inverter(VSI)	49.53	81.62	157.84
10	Direct Torque control of IM with Fuzzy Logic Controller using 2-level voltage source inverter(VSI)	49.53	61.82	137.14

Figure 8: Table 3 :

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