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Improving the Performance of CSI fed PMSM at Low Speed Operation

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ABSTRACT

This paper presents a sensorless direct torque control method for CSI fed Permanent Magnet Synchronous Motor (PMSM). The speed control of the system is obtained by using the compensation of stator flux. The flux error deviation is due to variation of stator resistance. The flux and torque error is used to measures the DTC logical control. The principles of Direct Torque Control (DTC) for selection of stator current vectors directly proportional to the difference between reference torque vector and reference stator flux linkage and their permanent values. There are a number of methods available to compensate the error in the system. Now we are introduced very first time without compensation of the stator resistance. The estimation doesn't depend on the motor parameters and except without changing stator resistance. Permanent-magnet synchronous machines are extensively used in servo drives because of its advantages such as high efficiency, high power density, maintenance free and torque ratio. In the respective computer simulation hysteresis comparators are used to compare the difference between biased reference values of stator flux and torque are equated on the values calculated from motor parameters. A novel PI Control method is used to compensate the stator flux variation and the simulation results and hardware results are prove that the performance of the CSI fed PMSM has been improved.

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INTRODUCTION

Permanent-magnet machines are extensively used in servo drives containingmachines with low power for machine-tool such as spindle motors, positioning drivesetc.) and robotic applications, but large machines up to 1 MW have also beenbuilt; for example, a 1 MW machine has been used in a ship propulsion drive[1].In the synchronousmotor drive with a load-commutatedcurrent-source inverter a constant frequency mains power is rectified by a controlledrectifier, and a controlled d.c. voltage is obtained. Alarge d.c. link inductor filtersthe d.c. link current, and the machine side inverter (load-commutated CSI inverter)is thus supplied by a constant current [2] [17]. Load commutation is ensured by over excitationof the synchronous motor to yield a leading power factor. The drive caninherently operate in all the four quadrants; the switching frequency of the inverterdetermines the motor speed. When the effects of commutation are neglected, thestator-current waveforms are analogous to those of the CSI-fed induction machine[17].

Structure of CSI fed PMSM:

The CSI fed PMSM drive system is shown in Fig.1. The current source rectifier is modeled as regulated voltage source.

In this paper, the effect of stator flux variation is discussed for CSI-FED PMSM and the stator flux is estimated with comparing the actual and estimated $R_s$by using a PI estimator. A signal proportional to stator resistance change is developed using the error between the reference and actual stator flux linkage. The performance of the controller is examined by both extensive simulation and experimental studies.

Mathematical Model of PMSM:

The drive scheme contains an electromagnetic torque and stator subtransient flux-linkage estimator[2]. The electromagnetic torque can be estimated from the terminal quantities by considering that, according to equation

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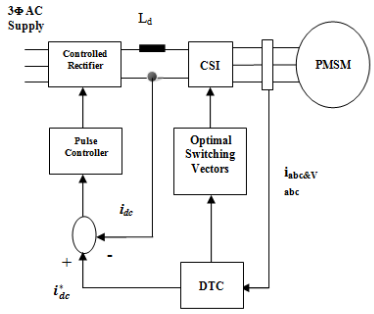

Fig. 1: Drive system with the CSI and PMSM.

$T_e= \frac{3}{2}p(L_s i_s + L_m i_r)\times i_s = \frac{3}{2}p\lambda_s \times i_s$ (1)

It is produced by the interaction of the stator flux linkages and stator current[8]. By using spacevectors in the stationary reference frame, and also considering that in the permanent magnet synchronous machine the stator flux-linkage space vector (λ_s) is equal to the subtransient stator flux-linkage space vector $\lambda_s'' + L_s'' i_s$ where L_s'' is the subtransient inductance is obtained, since $\lambda_s''= \lambda_{ds}+ j\lambda_{qs}$ and the vectorial product $L_s'' i_s \times i_s$,=0[17].

$T_e= \frac{3}{2}p(\lambda_{ds}i_{sq}-\lambda_{qs}i_{sd})$ (2)

The stator flux linkages (not the subtransient stator flux linkages) in the rotorreference frame can be estimated by using the stator currents i_{ds} and i_{qs} as

$\lambda_{ds}= L_{ds}i_{ds}+ \lambda_M$ (3)

$\lambda_{qs}= L_{qs}i_{qs}$ (4)

$V_{ds}= R_s i_{ds} + \frac{d}{dt}(\lambda_{ds}) - \omega_r\lambda_{qs}$ (5)

$V_{qs}= R_s i_{qs} + \frac{d}{dt}(\lambda_{qs}) - \omega_r\lambda_{ds}$ (6)

Where,

λ_{ds} = d axis stator magnetic flux,
λ_{qs} = q axis stator magnetic flux,
λ_M = rotor magnetic flux,
L_{ds} = d axis stator leakage inductance,
L_{qs} = q axis stator leakage inductance,
R_s = stator winding resistance,
T_e = electromagnetic torque,
p =differential operator,

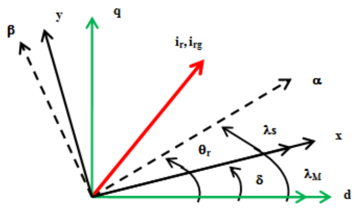

Fig. 2: Stator and rotor magnetic fluxes in different reference systems.

In general,when the synchronous machine has damper windings, the subtransient directandquadrature-axis inductances, L_{ds}'' and L_{qs}'' are not equal; thus L_s'' is not equalto the transient inductance(L_s'), but an approximation can he made by assumingthat

$L_s''\approx (L_{ds}''+ L_{qs}'')/2$ (7)

This is a good approximation if the subtransient saliencyin the two axes is not much different. In equation (2) $\lambda_s''=\lambda_{ds}+ j\lambda_{qs}$ is thesubtransient flux-linkage space vector (stator flux linkage behind the subtransientinductance), and $i_s=i_{ds} + ji_{qs}$ is the stator-current space vector, and both vectorsare expressed in the stationary reference frame. The stator currents and statorvoltages are monitored and the stator subtransient flux-linkage space vector can be obtained by

$\frac{d\lambda_s''}{dt} = V_s - R_s i_s - L_s'' \frac{di_s}{dt}$ (8)

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whereL_s''isthe subtransient inductance. The derivative in eqn(5) is a back e.m.f. Thus the stator subtransient flux-linkage components areobtained as

$$\lambda_d = \int (V_{ds} - R_s i_{ds} - L_s'' \frac{di_{ds}}{dt})dt$$
$$= \int (V_{ds} - R_s i_{ds})dt - L_s'' i_{ds} \quad (9)$$

$$\lambda_q = \int (V_{qs} - R_s i_{qs} - L_s'' \frac{di_{qs}}{dt})dt$$
$$= \int (V_{qs} - R_s i_{qs})dt - L_s'' i_{qs} \quad (10)$$

The angle γ(which is the angle between the space vectors $\lambda_s''$and i_s)can beestimated by using i_{ds}, i_{qs}, λ_d, and λ_q. The electromagnetic torque and thesubtransient stator flux-linkage space vector can be obtained in other ways aswell.

Using the transformation in equation (8) and Fig.2

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} Cos\delta & -Sin\delta \\ -Sin\delta & Cos\delta \end{bmatrix} \begin{bmatrix} i_x \\ i_y \end{bmatrix} \quad (11)$$

Where,

i_d and$i_q$are d and q axes currents

The main feedback signal in direct torque control algorithm is the estimated flux and torque.

$$\lambda_{qs}/|\lambda_s| = Sin\delta$$
$$\lambda_{ds}/|\lambda_s| = Cos\delta \quad (12)$$

Table I: Current Switching Vector Table.

ΔT_e	S_1	S_2	S_3	S_4	S_5	S_6
i	i_3	i_4	i_5	i_6	i_1	i_2
0	0	0	0	0	0	0
-i	i_6	i_1	i_2	i_3	i_4	i_5

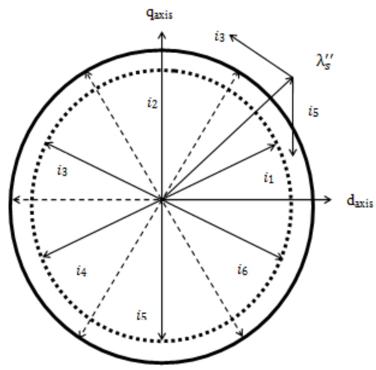

Fig. 3: Six Switching Current Vector.

Flux and Torque Estimator:

If the rotor position (Θ_r) is also measured, then the stator-current space vector in the rotor reference frame can he obtained from the stator-current space vector in the stationary reference frame as θr [14]

$$i_s' = i_{ds} + ji_{qs} = i_s \exp(-j\Theta_r)$$
$$= (i_{ds} + ji_{qs})\exp(-j\Theta_r) \quad (13)$$

The stator flux linkages (not the subtransient stator flux linkages) in the rotor reference frame can be estimated by using the stator currents i_{ds} and i_{qs}as

$$\lambda_{ds} = L_d i_{ds} + L_{md} i_F$$
$$= L_{s1} i_{ds} + L_{md}(i_{ds} + i_F) \quad (14)$$
$$\lambda_{qs} = L_{qs} i_{qs} \quad (15)$$

wherei_F is the measured field current, $L_{qs}$is the total direct-axis inductance, $L_{ds}= L_{s1}+ L_{md}$, L_{s1} is the stator leakage inductance, L_{md} is the d-axis magnetizing inductance, and L_{qs} is the q-axis inductance. To obtain greater accuracy, the variations of the inductances with the currents should also be considered. Thus if cross-saturation coupling is neglected then in general L_{md} varies with the d-axis magnetizing current: $i_{md}= i_{ds} + i_F$. Furthermore, $L_{qs} = L_{s1} + L_{mq}$ varies with the q-axis magnetizing current: $i_{mq}, = i_{qs}$. Thus $L_{md} = L_{md}(i_{md})$, $L_{mq} = L_{mq}(i_{mq})$. Therefore the stator flux-linkage components in the rotor reference frame can be expressed as

$$\lambda_{ds} = L_d i_{ds} + L_{md} i_F$$

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$= L_{s1} i_{ds} + L_{md} (i_{md}) (i_{ds} + i_F)$ (16)
$\lambda_{qs} = L_{qs} i_{qs} + L_{mq} (i_{mq}) i_{sq}$ (17)

The stator flux-linkage space vector in the stator reference frame can be obtained from

$$\lambda_s = \lambda_s' \exp(j\Theta_r)$$

$$\lambda_s = (\lambda_{ds} + j\lambda_{qs}) \exp(j\Theta_r) \quad (18)$$

Finally the subtransient flux - linkage space vector can be obtained from

$$\lambda_s'' = \lambda_d + j\lambda_q = \lambda_s - L_s'' i_s \quad (19)$$

However, enhanced performance at low frequencies can be achieved if = the obtained & is added to T ($V_s - R_s i_s$), where T is appropriately chosen, and then the resulting component is multiplied by $1/(l + pT)$, where p $= d/dt$. Thus

$$\bar{\lambda}_s = \frac{\lambda_s + T(V_s - R_s i_s)}{1 + pT} \quad (20)$$

It should be noted that in $V_s - R_s i_s$ is the rate of change of the stator flux-linkage space vector obtained from the measured stator voltages and currents. Thus it is obtained by using the stator voltage equation, which gives accurate estimation at higher stator frequencies. It follows that the stator subtransient flux-linkage space vector can be more accurately estimated by considering

$$(\bar{\lambda}_s'') = \bar{\lambda}_s - L_s'' i_s \quad (21)$$

and the thus obtained λ_d and λ_q could be-used for a more accurate estimation of the angle γ (which is the angle between λ_s'' and i_s). The electromagnetic torque can then be obtained as

$$t_e = \frac{3}{2} P(\bar{\lambda}_s'') \times i_s \quad (22)$$

The block diagram of flux estimator based on the equations (3) and (4) is shown in Fig. 4.

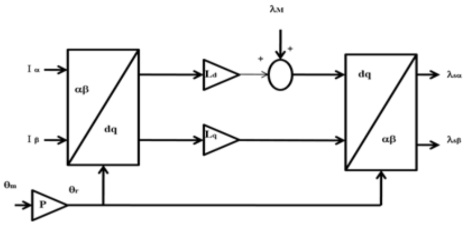

Fig. 4: Current model for flux vector estimator.

The relation between load incremental and error in torque and angle $\Delta\delta$ is nonlinear. The PI controller which generates the load angle increment required minimizing the instantaneous error between referenceT_{eref} and actual $T_e$torque has applied.

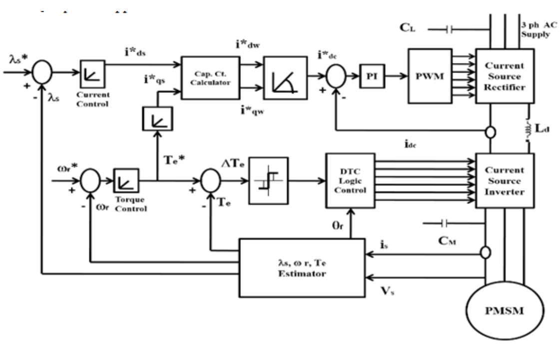

Fig. 5: Proposed diagram for DTC fed PMSM Drive System.

The estimation of the stator flux vector as

$$\lambda_s = \sqrt{\lambda_{ds}^2 + \lambda_{qs}^2} \quad (23)$$

$$\Theta_s = \tan^{-1}(\lambda_{qs}/\lambda_{ds}) \quad (24)$$

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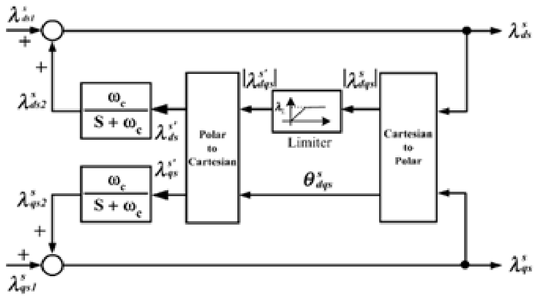

Fig. 6:.Flux Compensation. Shows the stator flux compensation from estimated flux and the reference flux values.

PI Controller:

PI controller will eliminate steady state error and forced oscillations resulting in operation of P controller andon-off controller. However, introducing integral mode has a negative effect on speed of the response and overall stability of the system. It can be expected since PI controller does not have means to predict what will happen with the error in near future. The PI controller will not increase the speed of response in the system during transient period. This problem can be solved by introducing derivative mode which has ability to predict what will happen with the error in near future and thus to decrease a reaction time of the controller.PI controllers are very often used in industry, particularly when speed of the response is not a problem. A controller without D mode is used when:

- large transport delays in the system
- large noise anddisturbances are present during operation of the process
- there is only one energy storage in process (inductive orcapacitive)
- system does not required fast response

RESULTS AND DISCUSSION

The performance of the CSI fed PMSM drive is analysed using MATLAB/SIMULINK model. When the torque suddenly gets change, the speed of the PMSM also gets changes.However the speed has to be maintained as constant in PMSM.The simulation results shows that without compensating the Rs the speed gets changes when torque changes.This is overcomed by compensating the λ_s.In our proposed method the speed is maintained as constant for changing torque even at low speed operation also.This can be achieved by compensating the stator flux.The uncompensated and compensated results are shown below for analysis poin of view:

1. Simulation results— to study the performance of the PI flux estimator with direct torque control strategy; the simulation of the system was proved by using MATLAB/SIMLINK. All the simulations were performed on a 3.5Kw, 4 pole PMSM motor as shown in Appendix. Fig. 7 (a) and 7(b) shows that the simulation results for stator flux of DTC drive CSI fed PMSM operated with 200 r/min and standstill with actual stator fluxλs respectively and Torque is oscillated when the λs is uncompensated. So mismatch between the controller set stator flux and its actual value can make the drive system unstable. So the stator flux compensation is essential to overcome instability. Extensive simulation has been performed to investigate the effect of stator flux variation on the performance of the controller Fig. 7 (c) shows the simulation result for torque and Fig. 7 (d) shows the simulation result for rotor speed during flux is uncompensation.

a) Without Compensation:

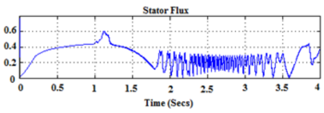

Fig. 7: (a).Simulation Results for Stator Flux.

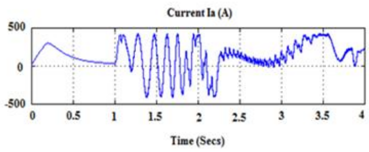

Fig. 7: (b). Simulation Results for Stator Current.

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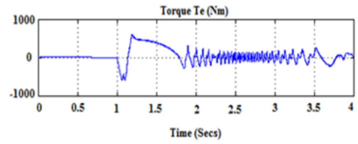

Fig. 7: (c). Simulation Results for Torque.

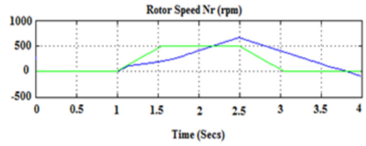

Fig. 7: (d). Simulation Results for Rotor speed.

b) With Compensation:

All the simulations were performed on a 3.5Kw, 4 pole PMSM motor as shown in Appendix. Fig. 8 (a) and 8(b) shows that the simulation results for stator flux of DTC drive CSI fed PMSM operated with 200 r/min and standstill with actual stator fluxλs respectively and Torque is controlled when the λs is compensated. DTC logic controller gives the gate pulse to the inverter to control the output current and voltage of the system. So the stator flux compensation is essential to overcome instability of the system.

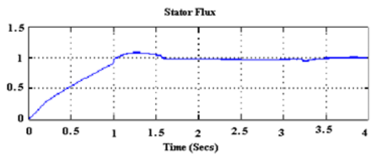

Fig. 8 (a): Simulation Results for Stator Flux.

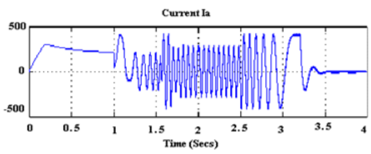

Fig. 8 (b): Simulation Results for Stator Current.

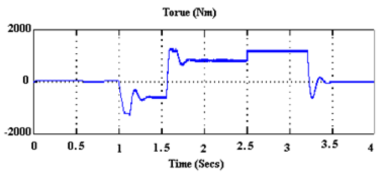

Fig. 8 (c): Simulation Results for Torque.

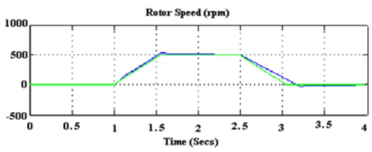

Fig. 8 (d): Simulation Results for Rotor speed

2. Experimental Results:

The effectiveness of the proposed sensorless drive scheme was tested experimentally. The block diagram of the sensorless drive is shown in Fig. 9. The mechanical part of the drive contains the PMSM and a loading DC motor. A Free scale DSP 56F8037 digital signal processor is used to carry out the real-time algorithm. A three-

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phase insulated gate bipolar transistor intelligent power module is used for an inverter. The coding of real-time control software was done using C language.

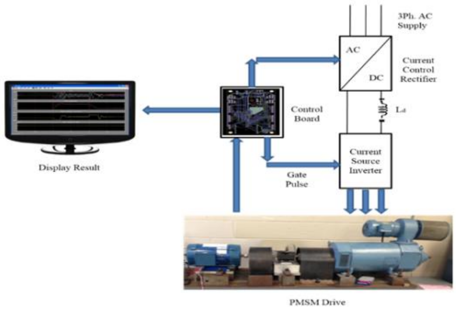

Fig. 9: Block diagram for experimental set up.

All measured and controller internal variables are accessible through the serial link to the PC, where graphical data-analysis software can be run. The sampling time of the measurements and computation of control algorithm are both 200 μs. The controllers of quantities in the control structure of the AC drive were adjusted accordance with the parameters are used in PMSM is shown in *Appendix.*

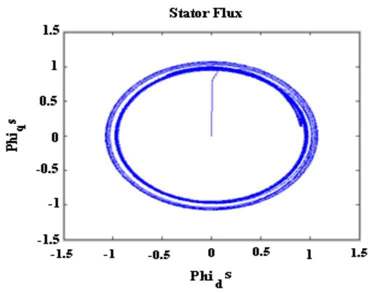

Fig. 10 (a): Before Stator Flux Compensation.

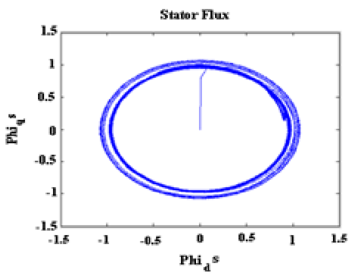

Fig. 10 (b): After Stator Flux Compensation.

The low-speed reversal from -200 to +200 with full load is shown in Fig. 10(a). The reference speed, actual speed, reference torque and actual torque are shown. The actual speed follows the reference speed very closely during the transient interval. The dynamic response during acceleration from standstill to 200r/min is shown in Fig. 10(b). The machine was originally operated at zero speed with step load the estimation error is very small in steady state and becomes higher at points of load changes, which occur very fast. Otherwise, zero speed is holding satisfactorily. The estimated speed tracks the actual speed closely during the transient and steady state and also show that ripples of torque is minimized.

Conclusion:

PI control of stator flux estimator of PMSM drives has been presented in this paper:

- The stator flux is estimated using the error between stator flux$\boldsymbol{\lambda}$**s**estimated from measured stator current and voltage and its reference $\boldsymbol{\lambda}_s^*$. A signal proportional to stator flux change is developed using the error between the reference and actual stator flux linkage. The error is processed through a PI controller.

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- It is shown that the DTC drive system can become unstable if the controller resistance differs from that of actual machine flux.
- An adaptive PI stator flux compensator is designed and applied to eliminate the effect of stator flux variation in DTC controlled PMSM motor drives. The performance of the compensator is examined by extensive dynamic simulation.
- The PI flux compensator shows a promising performance for the stator flux compensation. The design and implementation of a PI flux estimator is easier compared to other controller.

Appendix:

Number of pole pairs	4
Stator Resistance	0.22Ω
Magnetic Flux	0.175 Wb
Voltage	380 v
Base speed	1500rpm
Electromagnetic Torque	22 Nm
D axis Inductance (Ld)	8.5e-03
Q axis Inductance (Lq)	8.5e-03

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