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On Line Stator Resistance Error Compensation for CSI Fed PMSM Drive

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Abstract

This paper presents an online stator resistance estimator to achieve precise torque control of CSI fed PMSMs over a low speed operating region. A quick and precise control several researchers have proposed implementations combining the use of permanent magnet synchronous motor with the direct torque control (DTC) technique. The electromagnetic torque, stator flux and rotor position can be estimated using the measured stator voltage and currents in direct torque control. The estimation does not depend on motor parameter except the stator resistance. The variation of stator resistance due to changes in temperature or low speed operation and degrade the performance of DTC controller by introducing errors in the estimated flux linkage magnitude, position and the electromagnetic torque. So the compensation for the effect of stator resistance variation then becomes necessary. In this paper investigates the effect of variation of stator resistance on DTC) scheme applied in a current source inverter (CSI) fed Permanent magnet synchronous motor drive system.. A method of stator resistance estimation using a proportional-integral (PI) estimator has been proposed in this paper.

Keywords: Current source Inverter, PM synchronous Motor, Direct torque control and Stator resistance compensation.

Introduction
Simple converter structure, motor-friendly waveforms, inherent four-quadrant operation capability, and reliable short-circuit protection are features that make current-source inverter (CSI) (Figure 1) well suited for medium-voltage drives applications [1-3]. Zero-speed operation plays an important role in applications such as cranes, hoists, and traction drives, where maintaining the desired torque down to zero speed or starting the load with a high torque from zero speed is highly desirable. Recent work has focused on control strategies [4]–[8], PWM schemes [9]–[12], topologies [13]–[16], and efficiency [17], [18] for high-power current-source

converters and drives, where significant improvements have been achieved, such as harmonic distortion minimization, high input power factor, minimized dc-link current, and reduced switching frequencies. However, it seems that zero-speed operation of the high-power PWM CSI-fed PMSM drive has seldom been reported.

In recent years, DTC has become one of the favored control schemes for induction motors [19,20,21,22]. In DTC scheme, controlling the amplitude and rotational speed of the stator flux controls the torque. The same principle has been applied in Interior Permanent Magnet Synchronous Motors by the authors [23,24,25]. DTC is capable of producing fast torque response in spite of its simplicity. But the main limitation of DTC is the use of stator resistance for the estimation of stator flux [2]. The variation of stator resistance due to temperature and frequency degrade DTC controller performance at low speed. The DTC controller at low speed can be made more reliable if the stator resistance is estimated during operation of machine. The stator resistance changes mainly due to temperature variation (Figure ure.2). Such changes deteriorate the drive performance by introducing errors in the estimated magnitude and position of the flux linkage vector. This in turn affects the estimation of the electromagnetic torque, particularly at low speeds. The stator resistance voltage drop is relatively large at low speeds and may become comparable to the back emf. If the stator resistance deviates from the one used in the controller, the drive may become unstable at low speed. Several control schemes have been proposed to overcome the problem of stator resistance variation which has some shortcomings such as restriction to speed control range of the drives and problem of convergence [26,27,28,29,30]. In this paper, the effect of stator resistance variation is discussed and the stator resistance is estimated 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 extensive simulation studies. Simulations show that the drive system becomes unstable if the stator resistance value used in the controller differs from that of the machine actual resistance.

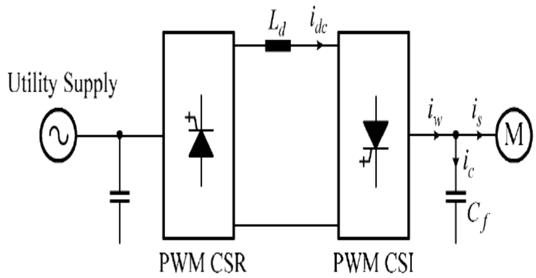


Figure 1: Conventional CSI fed Drive.

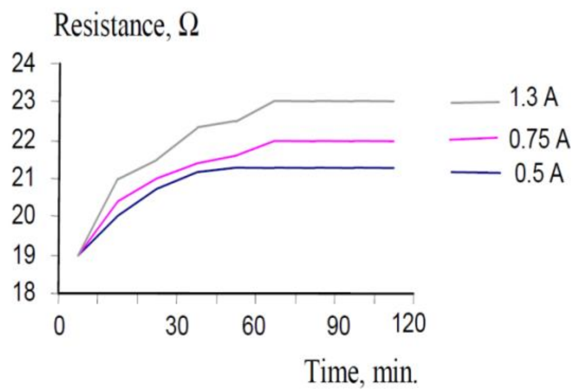


Figure 2: The Variation of Stator Resistance.

Mathematical Model of PMSM

Stator magnetic flux vector $\boldsymbol{\lambda_S}$ and rotor magnetic flux vector $\boldsymbol{\lambda_M}$, can be represented on rotor flux (dq), stator flux (xy) reference system as shown in Figure 3.The angle between the stator and rotor magnetic fluxes is **δ**, called load angle. **δ** is constant for a constant load torque. In that case both the stator and the rotor fluxes rotate at constant speed. However under different loads **δ** varies. Either the stator current rotation speed or the variation of **δ** is controlled in order to control the increase of the torque.

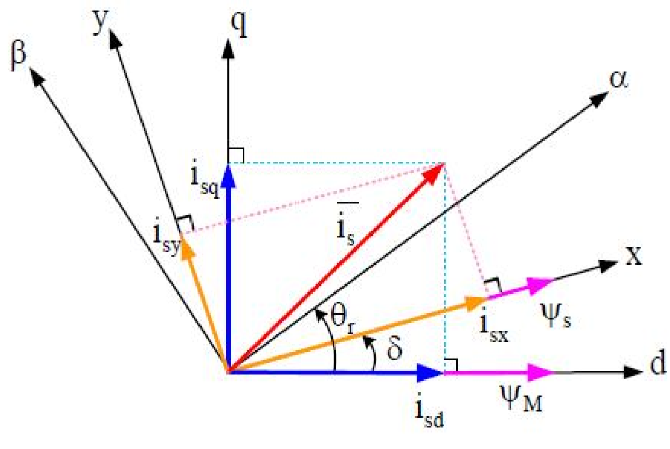


Figure 3: Stator and rotor magnetic fluxes in different reference systems.

$$\lambda_{ds} = L_{ds} i_{ds} + \lambda_M \quad (1)$$

$$\lambda_{qs} = L_{qs} i_{qs} \quad (2)$$

$$v_{ds} = R_s i_{ds} + \frac{d}{dt}\lambda_{ds} - \omega_r \lambda_{qs} \quad (3)$$

$$v_{qs} = R_s i_{qs} + \frac{d}{dt}\lambda_{qs} - \omega_r \lambda_{ds} \quad (4)$$

$$T_e = \frac{3}{2}P\left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}\right)$$
$$T_e = \frac{3}{2}p\left[\lambda_M i_{qs} - \left(L_{qs} - L_{ds}\right)i_{ds}i_{qs}\right] \quad (5)$$

is obtained [7]. The symbols of parameters are as follows;
$\boldsymbol{\lambda_{ds}}$ d axis stator magnetic flux,
$\boldsymbol{\lambda_{qs}}$ q axis stator magnetic flux,
$\boldsymbol{\lambda_M}$ rotor magnetic flux,
$\boldsymbol{L_{ds}}$ d axis stator leakage inductance,
$\boldsymbol{L_{qs}}$ q axis stator leakage inductance,
$\boldsymbol{R_s}$ stator winding resistance,
$\boldsymbol{T_e}$ electromagnetic torque,
$\boldsymbol{p}$ double pole number,

Using the transformation in equation (6) and Figure 3, the expressions (7) are obtained, using (7), equation (5), can be transformed into equation (8)

$$\begin{bmatrix} \boldsymbol{F_d} \\ \boldsymbol{F_q} \end{bmatrix} = \begin{bmatrix} \boldsymbol{cos\delta} & \boldsymbol{-sin\delta} \\ \boldsymbol{sin\delta} & \boldsymbol{cos\delta} \end{bmatrix} \begin{bmatrix} \boldsymbol{F_x} \\ \boldsymbol{F_y} \end{bmatrix} \quad (6)$$

Here F represents the voltage, current and magnetic flux.
Using Figure 3;

$$sin\delta = \frac{\lambda_{qs}}{|\lambda_s|}$$
$$cos\delta = \frac{\lambda_{ds}}{|\lambda_s|} \quad (7)$$

is obtained. The expression $|\lambda_s|$ represents the stator magnetic flux amplitude. When the necessary terms are placed using Figure 1, the following equation is obtained.

$$T_e = \frac{3}{2}p\left[\lambda_{ds}\left(i_{sx}sin\delta + i_{sy}cos\delta\right) - \lambda_{qs}\left(i_{sx}cos\delta - i_{sy}sin\delta\right)\right]$$
$$= \frac{3}{2}p\left[i_{sx}\frac{\lambda_{ds}\lambda_{qs}}{|\lambda_s|} + i_{sy}\frac{\lambda_{ds}^2}{|\lambda_s|} - i_{sx}\frac{\lambda_{ds}\lambda_{qs}}{|\lambda_s|} + i_{sy}\frac{\lambda_{qs}^2}{|\lambda_s|}\right]$$
$$T_e = \frac{3}{2}p|\lambda_s|i_{sy} \quad (8)$$

It is clear that electromagnetic torque is directly proportional to the y-axis component of the stator current [8]. Controlling directly y-axis component of the stator current provides appropriate selection of the voltage switching vectors. Depending on less parameter is the main advantage of stator current control. It is possible to say that in a practical application the estimation technique shown in equation (5) requires saturation-dependent inductances. Therefore in equation (8) direct torque control over the stator current control is more convenient.

DTC Scheme for PMSM

The basic principle of DTC is to select stator current vectors according to the differences between the reference and actual torque and flux linkage. The current controller followed by a pulse width modulation (PWM) comparator is not used in DTC system, and the parameters of the motor are also not used, except the stator resistance. Therefore, the DTC possesses advantages such as lesser parameter dependence and fast torque response when compared with the torque control via PWM current control method. Figure 4 shows the block diagram of the DTC for Permanent Magnet Synchronous Motor (PMSM) drive with a stator resistance estimator. In DTC, the stator flux is estimated by using the equation (9) and (10), taking the integral of difference between the input voltage and the voltage drop across the stator resistance as,

$$\lambda_{ds} = \int\left(v_{ds} - \hat{R}_s i_{ds}\right) dt \tag{9}$$

$$\lambda_{qs} = \int\left(v_{qs} - \hat{R}_s i_{qs}\right) dt \tag{10}$$

The flux linkage phasor is given by

$$\lambda_S = \sqrt{\left(\lambda_{ds}^2 + \lambda_{qs}^2\right)} \tag{11}$$

$$\angle\theta_S = tan^{-1}\frac{\lambda_{qs}}{\lambda_{ds}} \tag{12}$$

and the electromagnetic torque is given by the equation,

$$T_e = \frac{3}{2}P\left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}\right) \tag{13}$$

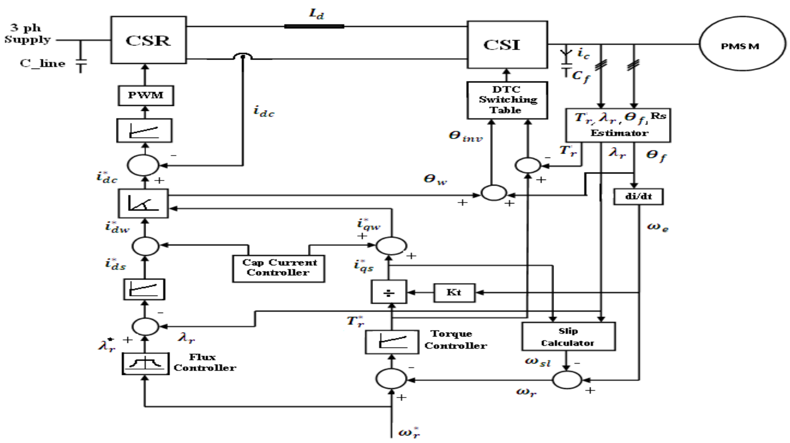


Figure 4: Proposed diagram for DTC fed PMSM Drive System.

Where
λ_{ds} - *d*-axis flux linkage.
λ_{qs} - *q*-axis flux linkage.
$\hat{R}_s$ - estimated stator resistance.
P - number of pole pairs

Effect of Stator Resistance Variation

In DTC, the stator flux is estimated using the equation

$$\lambda_s = \int (V_S - R_S I_S)dt \tag{14}$$

Where $\boldsymbol{\lambda_s}$, **Vs** and $\boldsymbol{I_S}$ represent the stator flux linkage, voltage and current vectors respectively. The variation of ***Rs*** may influence the calculation of stator flux significantly and thereby the overall performance of the DTC system. At low speeds, the back emf term is small, and the resistive drop ***RsIs*** is comparable with the supply voltage magnitude ***Vs***. Therefore any change in stator resistance gives wrong estimation of stator flux and consequently of the electric torque and the stator flux position. An error in stator flux position is more important as it can cause the controller to select a wrong switching state which can result in failure of the controller. At high speeds, the stator resistance drop ***Is Rs*** is small and can be neglected. If increase stator resistance the stator current, flux and torque are oscillated. So a mismatch between the controllers set stator resistance and its actual value can create instability. So the parameter mismatch between the controller and motor makes the drive system unstable. So the stator resistance compensation is essential to overcome instability in DTC controlled PMSM drive system.

Pi Stator Resistance Estimator

The block diagram of PI stator resistance compensator is shown in Figure 5. The error in the stator flux is used as an input to the PI estimator. The technique is based on the principle that the change in stator resistance will cause a change in stator current and stator flux linkage $\boldsymbol{\lambda_S}$. The error between the stator flux linkage $\boldsymbol{\lambda_S}$ and its reference $\boldsymbol{\lambda^*_S}$ is proportional to the stator resistance change. The equation for PI resistance estimator is given by

$$\Delta R_S = \left(K_P + K_I \frac{1}{S}\right) \Delta\lambda_S$$

Where K_P and K_I are the proportional and integral gains of the PI estimator.

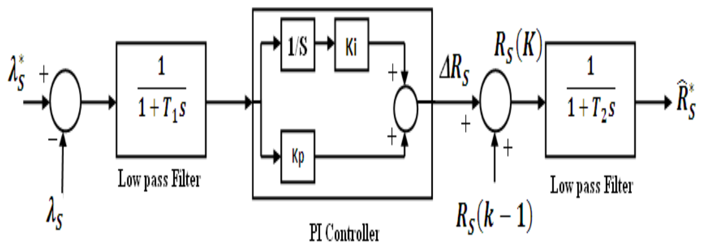


Figure 5: Block Diagram for PI Stator resistance compensation.

The error between the estimated stator flux **λs** and its reference $\boldsymbol{\lambda_S^*}$ is passed through a low pass filter with a very low cutoff frequency in order to attenuate high frequency component contained in the estimated stator flux. This filter time constant should be small compared to the stator resistance estimator time constant to overcome its effect on the stator resistance adaptation. Then the signal is passed through a PI estimator. The output of the PI estimator is the required change of resistance ΔR_S due to change in temperature or frequency. The change of stator resistance ΔR_S is continuously added to the previously estimated stator resistance $R_S(k-1)$. The final estimated stator resistance $\hat{R}_S$ is again passed through a low pass filter to have a smooth variation of stator resistance value. This updated stator resistance can be used directly in the controller.

Results and Discussions

To study the performance of the PI resistance estimator with direct torque control strategy, the simulation of the system was proved by using MATLAB/SIMLINK. All the simulations were performed on a 4 pole PMSM motor as shown in Appendix. Figure 6 shows that the drive performance under step torque variation, the simulation results for DTC drive CSI fed PMSM operated with high speed about 1500 rpm and torque is 792 NM with actual stator resistance Rs. Figure 7 shows that the flux locus is to drift away from the origin and Torque & speed are oscillated when the machine operated at low speed with stator resistance Rs and speed drops 10 r/min and goes back to steady state within 0.2 s.. This is due to mismatch between the controller set stator resistance and its actual value can make the drive system unstable. So the stator resistance compensation is essential to overcome instability. In actual operating conditions, the rate of change of temperature is very slow and so the stator resistance changes. Figure 8 shows that the response in a stator resistance compensated torque drive system with low speed operation. The Stator resistance is increased by $2R_S$ of its nominal value. It is seen from Figure 8 that the flux and torque response is very good and the speed drop is reduced to 10 rpm to 2rpm with slight increase of the speed recovery overshoot..

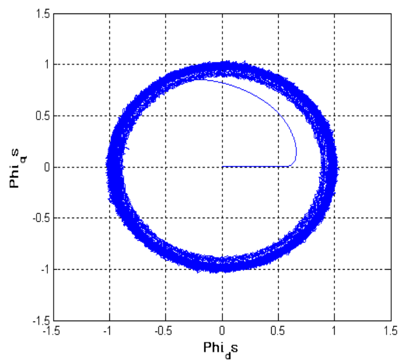


Figure 6 (a)

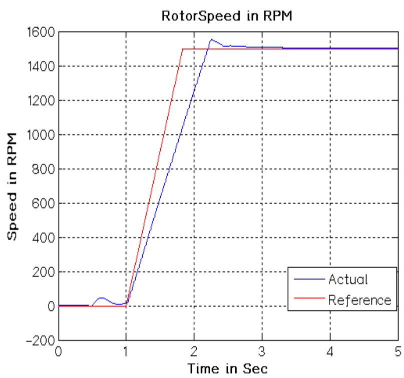


Figure 6 (b)

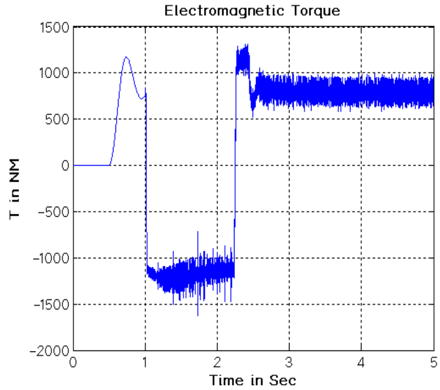
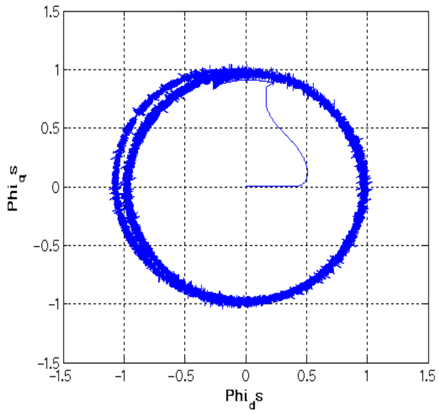


Figure 6 (c)

Figure 6: Simulation results for high speed operation (a). Stator flux,(b). Rotor Speed, (c). Torque.



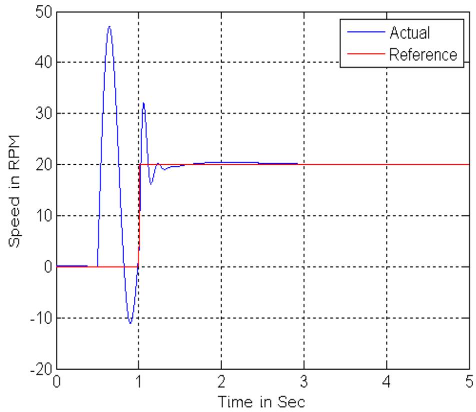


Figure 7 (a) **Figure 7 (b)**

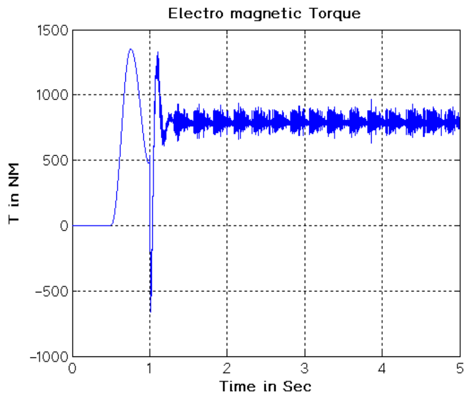


Figure 7 (c)

Figure 7: Simulation results for low speed operation without Rs compensation (a). Stator flux, (b). Rotor Speed, (c). Torque.

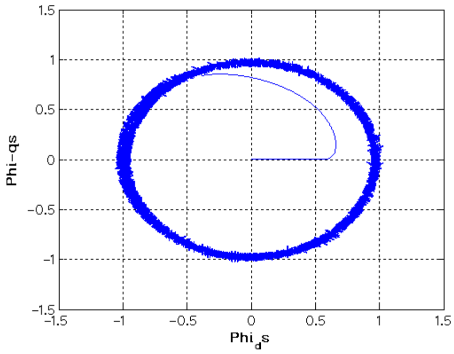


Figure 8 (a)

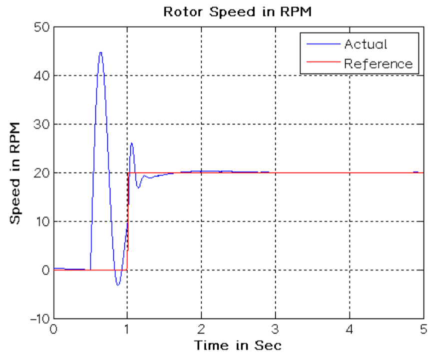


Figure 8 (b)

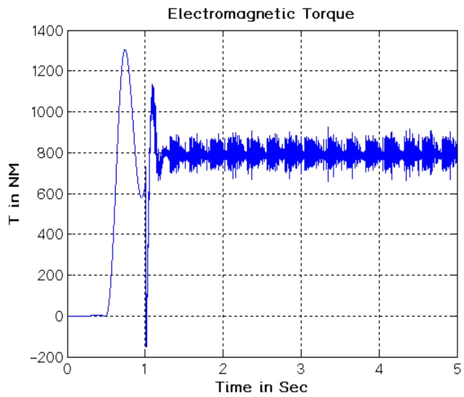


Figure 8 (c)

Figure 8: Simulation results for low speed operation with Rs compensation (a). Stator flux, (b). Rotor Speed, (c). Torque.

Conclusion

The online estimation of the stator resistance of an induction machine from electrical measurements at the stator terminals has been proposed. The stator resistance is estimated using the error between stator flux **λs** estimated from measured stator current and voltage and its reference $\boldsymbol{\lambda}_s^*$ A signal proportional to stator resistance change is developed using the error between the reference and actual stator flux linkage. In this study a stator resistance has been compensated through PI controller and verified. Before proposing this method It is shown that the DTC drive system can become unstable if the controller resistance differs from that of actual machine resistance. An adaptive PI stator resistance compensator is designed and applied to eliminate the effect of stator resistance variation in DTC controlled PMSM motor drives. Due to the accurate and reliable estimation of the stator resistance, such a drive is particularly suitable for low-speed operation, as demonstrated by MATLAB / simulink results. The PI resistance compensator shows a promising performance for the stator resistance compensation. The design and implementation of a PI resistance estimator is easier compared to the Fuzzy/Neural controller.

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Appendix

Table 1: Data of PMSM.

Number of pole pairs	2
Stator Resistance	2.01e-03Ω
Magnetic Flux	0.9 Wb
Voltage	460v
Base speed	1500rpm
Electromagnetic Torque	792

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