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MTPA based Sensorless Field Oriented Control of PMSM using MRAS

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Abstract

Knowledge of rotor speed and rotor position are essential for effective functioning of Field Oriented Control (FOC) technique. But this requires sensors which not only impacts the reliability of the drive but also increases the cost and size of the drive. In this paper, a Sensorless Field Oriented Control of Permanent Magnet Synchronous Motor (PMSM) with Maximum Torque per Ampere (MTPA) principle is evaluated. Model Reference Adaptive System (MRAS) based on Stator current model is used as rotor position estimation algorithm which is one of the simpler and accurate estimation techniques. MTPA principle is applied in both sensor and sensorless modes and the dynamic performance of the drive is validated under varying load and speed conditions. Results have proved the feasibility and effectiveness of sensorless control compared to controller with sensors.

1. Introduction

Permanent Magnet Synchronous Motor (PMSM) is gaining more importance mainly due to its attractive features such as high power density, high efficiency, high torque to weight ratio and so on [1][2][3]. PMSM is one of the fastest growing members of the variable speed drive family and is extensively studied among researchers, scientists and engineers [3]**.** Maintenance free operation, robustness against environment, compact size, high controllability are some more features of PMSM that are responsible for its wide utilization in traction applications such as electric vehicles and hybrid EVs [2][4][5]; in domestic appliances like washing machine etc.

Right motor control technique is often essential for driving such high efficient PMSM. Speed control is quite challenging due to variations in load and time varying motor parameters. Several speed control methods have been proposed in literature. They are broadly classified into scalar and vector control techniques. In scalar control, magnitude of voltage is varied in line with frequency in a constant ratio such that the motor is neither over-excited nor under-excited [6]. It is widely used in variable speed industrial drives because of its merits such as cost effectiveness, easy implementation [7]**.** However the major drawback with this control is sluggish response and poor dynamic performance [7].Vector Control or Field Oriented Control (FOC) allows independent control of flux and torque identical to separately excited DC machine. Another advanced scalar control technique is Direct Torque Control (DTC) where a direct control of torque and flux is achieved by selecting the appropriate voltage space vector. Both FOC and DTC techniques control the torque and flux such that motor accurately tracks them irrespective of parameter variations and any load disturbances [8].

Due to thermal and reliability constraints the maximum permissible current and voltage of the inverter are limited, thus limiting the torque capability [9]. Also it will cause the drift of stator current vector, thereby affecting the machine's power factor [10]. MTPA or i_d=0 control can enhance the torque output capability, minimizes the stator current and thereby copper loss and hence increases the overall operational efficiency of motor drive system [1]. Thus MTPA can increase current utilizing efficiency with minimum converter rating [9]. This simplified control strategy reduces the capacity requirements and current limits for inverters in Electric Vehicles [10]**.**

Control of PMSM using FOC with MTPA control improves dynamic response and provides good speed regulation. However for implementing FOC, exact position of Permanent Magnet Flux orientation is required [7][11]**.** The rotor position information is usually obtained by high resolution sensors such as optical encoders or electro-magnetic resolvers [4] attached to rotor shaft. However, the use of these position sensors increases the complexity, size, weight and cost of the system [9][12][13].

Elimination of these position sensors is highly encouraged to increase the reliability and robustness and reduce the cost of drive [9] and this has been a driving factor behind many sensorless techniques that are proposed in the literature. Sensorless Techniques are broadly classified into two categories [14]**,**

i) Based on motor model and

ii) Based on rotor saliency information.

The second category is ideally suitable for IPMSM drive whereas first category is based on stator current or voltage model and estimates the rotor speed and position. They can be either open-loop estimators or closed loop observer such as Extended Kalman Filter, Sliding Mode Observer, and MRAS. Out of different closed loop techniques, MRAS is known for its simplicity and it gives good estimation results [15][16][17]. In this work, MRAS based on stator current model is used and a good performance in-line with sensors is achieved.

2. Field Oriented Control of PMSM

FOC technique is based on transforming three phase time variant quantities to two phase time invariant quantities. Stator current model approach is applied in this work. By using simple PI regulators, it is possible to separately control the torque and flux producing components.

The main goal of this work is to implement FOC for PMSM by considering Maximum Torque per Ampere (MTPA) principle. PMSM is modelled in MATLAB/ Simulink environment; corresponding modelling equations for PMSM are given in Eqns (1) to (10).

The voltage equations are given by

$$V_d = R_s i_d + \rho\lambda_d - \omega_e\lambda_q \quad (1)$$

$$V_q = R_s i_d + \rho\lambda_q + \omega_e\lambda_d \quad (2)$$

The flux linkages λ_d and λ_q are given by

$$\lambda_d = L_d i_d + \lambda_f \quad (3)$$

$$\lambda_q = L_q i_q \quad (4)$$

On substituting the flux linkages from Eqns (3) and (4) in Eqns (1) and (2), voltage equations are obtained as

$$V_d = R_s i_d + L_d \frac{d}{dt} i_d - \omega_e L_q i_q \quad (5)$$

$$V_q = R_s i_q + L_q \frac{d}{dt} i_q + \omega_e L_d i_d + \omega_e \lambda_f \quad (6)$$

The electromagnetic torque of PMSM is given by

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left[\left(L_d - L_q\right)\left(i_d i_q\right) + \lambda_f i_q\right] \quad (7)$$

The rotor mechanical speed is obtained from the motor dynamics equation and is given by

$$J\frac{d\omega_m}{dt} + B\omega_m + T_L = T_e \quad (8)$$

3. Maximum Torque Per Ampere

As per electromagnetic laws, torque is produced due to interaction of two magnetic fields and is given by vector cross product of two magnetic fields.

$$T_{em} = B_{stator} \times B_{rotor} \quad (9)$$

Thus, maximum torque can be obtained by maintaining stator and rotor magnetic fields orthogonal to each other. MTPA strategy is being employed in this work to obtain maximum torque with minimum amount of stator current which in turn reduces copper losses for a given torque [9].

MTPA can be achieved in Surface mounted PMSM (SPMSM) by nullifying the flux along direct axis and concentrating the entire stator flux along quadrature axis. This can be obtained by forcing d-axis current to zero (i_d=0).

The electromagnetic torque equation under MTPA control (i_d=0) for SPMSM is given by

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left[\lambda_f i_q\right] \quad (10)$$

Thus from Eqn (10) it is observed that only quadrature axis current is maintained in proportion to torque requirement. As such, maximum desired torque is generated with minimum stator current reducing the copper losses and increasing the efficiency of the drive.

4. Need for Sensorless Control

The key for FOC to work is to know the rotor position information. This information is needed for transforming the time variant quantities from stationary frame to synchronously rotating reference frame. To obtain position information, optical encoders or sensors are used. Due to additional components, overall cost and size of the drive are increased. Moreover, certain appliances like electric traction are subjected to harsh/dirt environment and vibrations and usage of sensors lead to reliability issues. Thus, there is a necessity to remove such sensors and this has been a driving factor behind many sensorless control techniques proposed in the literature.

5. Model Reference Adaptive System

Model Reference Adaptive System (MRAS) has emerged as one of the widely used strategy due to its simplicity and ease in implementation. Similar to other estimation algorithm, MRAS also provides accurate estimation results. The basics of MRAS are to use two independent models: reference model which is independent of the variable to be estimated and another adjustable model which is dependent on the variable to be estimated. The adaptation mechanism uses the difference between the two signals to tune the estimated variable and feed it back to the adjustable model. The estimated value in this way is driven to its true value [17]. Illustration of Model Reference Adaptive System (MRAS) is as shown in Fig.1.

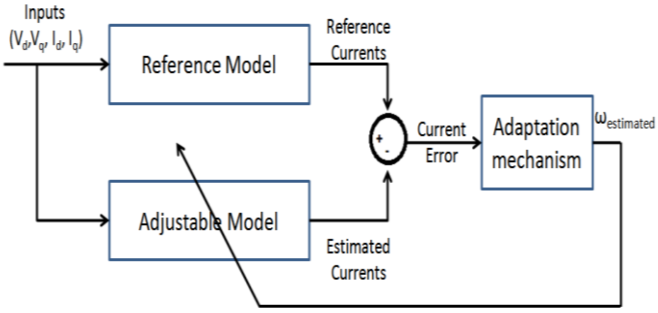

Fig. 1 Illustration of the Model Reference Adaptive System

In MRAS [18], rotor speed is estimated by making use of Eqn (11). Rotor position is obtained by integrating the rotor speed.

$$\hat{\omega}_e = \left(K_{pMRAS} + \frac{K_{iMRAS}}{s}\right)\left(i_d\hat{i}_q - i_q\hat{i}_d - \frac{\lambda_f}{L_s}\left(i_q - \hat{i}_q\right)\right) \quad (11)$$

Block Diagram of proposed work using MRAS as rotor position estimation algorithm is as shown in Fig.2

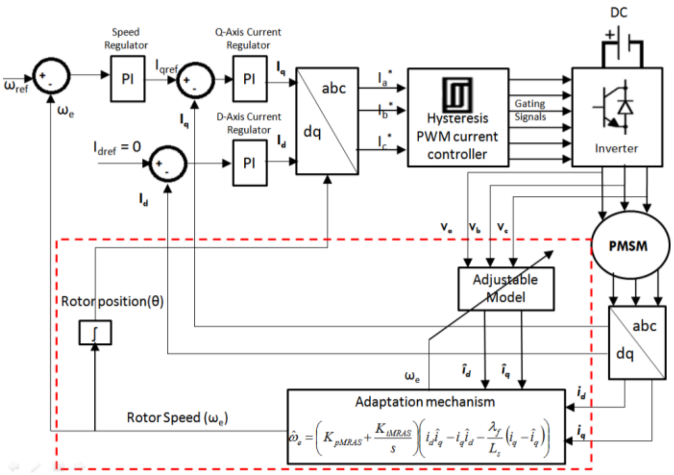

Fig. 2. Block Diagram of the proposed work using sensorless control

6. Results and Discussion

6.1. Case I : Constant Load and Variable Speed condition

A constant load torque of T_L= 6N.m is applied and the dynamic performance of the drive is tested with different speeds 1000 rpm at t=0; 2500 rpm at t=0.2sec; 3000 rpm at t=0.5sec; 2000 rpm at t=0.7sec and 1500 rpm at t=0.9sec respectively (i.e. constant torque mode of operation). The drive is tested when sensors are used for detecting the rotor speed and position information and the corresponding responses of stator current, direct axis current, quadrature axis current, electromagnetic torque, speed and flux waveforms with FOC are plotted in Fig.3. Similar conditions are applied by using MRAS technique as an estimation technique and responses are plotted in Fig.4.

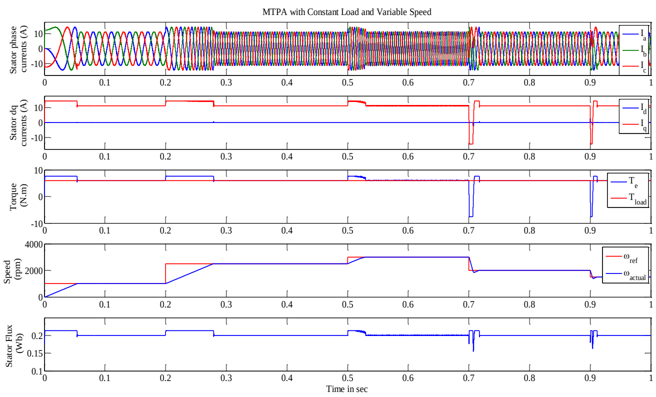

Fig 3. Responses of stator;direct,quadrature axis currents ,torque, speed and flux for MTPA with Constant load and Variable Speed using sensors

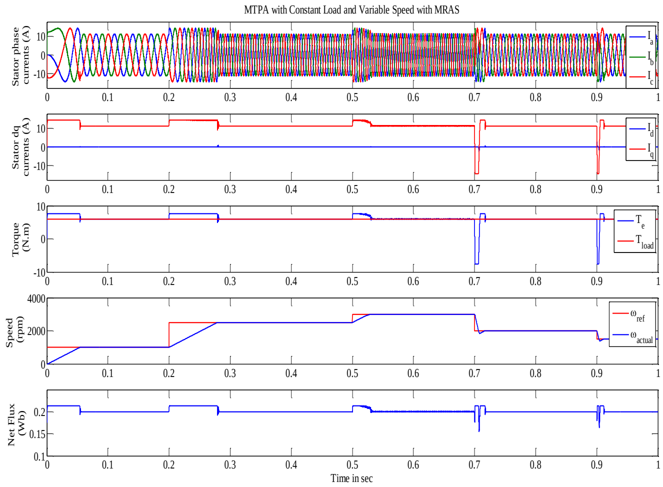

Fig 4. Responses of stator;direct,quadrature axis currents , torque, speed and flux waveforms for MTPA with Constant load and Variable Speed using sensorless control (using MRAS)

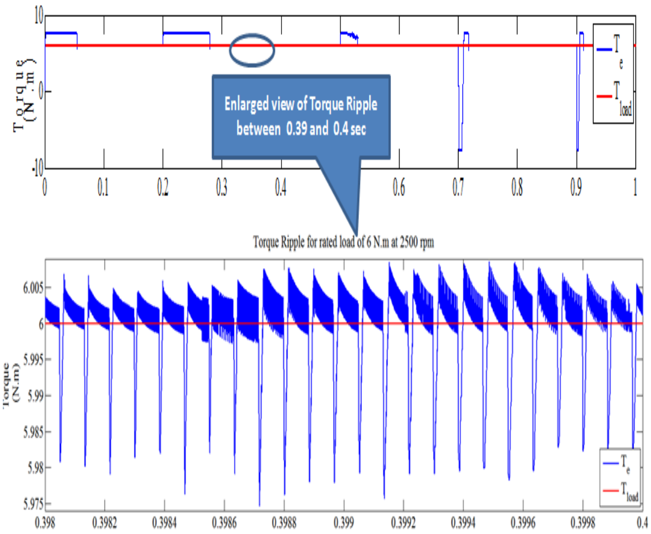

Fig 5. Enlarged View of Torque Ripple for Constant Torque of 6 N.m at 2500 rpm

Torque Ripple is calculated by using the Eqn (12)

$$\text{TorqueRipple(\%)} = \left(\frac{\text{MaximumValue} - \text{MinimumValue}}{\text{AverageValue}}\right) * 100 \quad (12)$$

For example, the torque ripple percentage for the sample waveform in Fig.5 is 0.61%. On similar lines, Torque Ripple and Flux Ripple percentages are calculated for both the modes for different speeds and are tabulated in Table 1 and Table 2. It is observed that torque ripple is slightly less in MRAS when compared to without MRAS technique whereas Flux Ripple is maintained nearly same in both the modes.

Table 1: Drive Performance at Constant Load T_L= 6 Nm Using Sensors

Time (sec)	Speed (rpm)	I_s (A)	I_d (A)	I_q (A)	Net Flux (Wb)	Torque Ripple (%)	Flux Ripple (%)
0	1000					0.30	0.10
0.2	2500					0.61	0.20
0.5	3000	11.44	0	11.44	0.2	1.56	0.45
0.7	2000					0.48	0.15
0.9	1500					0.38	0.10

Table 2: Drive Performance at Constant Load T_L= 6 Nm Using Sensorsless Control

Time (sec)	Speed (rpm)	I_s (A)	I_d (A)	I_q (A)	Net Flux (Wb)	Torque Ripple (%)	Flux Ripple (%)
0	1000					0.29	0.10
0.2	2500					0.56	0.15
0.5	3000	11.43	0	11.43	0.2	1.83	0.50
0.7	2000					0.45	0.15
0.9	1500					0.37	0.10

6.2. Case II : Constant Speed and Variable Load condition

A constant speed of 3000 rpm is applied and the dynamic performance of the drive is tested when load torque, T_L= 2N.m at t=0.1sec; T_L= 4N.m at t=0.3sec; T_L= 6N.m at t=0.5sec; T_L= 4N.m at t=0.7sec and T_L= 2N.m at t=0.9sec. Fig.6 and Fig.7 shows the responses of stator current, direct axis current, quadrature axis current, electromagnetic torque, speed and flux waveforms for both sensor and sensorless modes respectively.

Since the command speed is set at 3000 rpm, frequency of operation is constant in this case. MTPA control (i_d=0 control) is applied and as load torque is varied, quadrature axis current is changed in proportion as in Eqn (10).Torque Ripple and Flux Ripple percentages are calculated similar to Case I and are tabulated in Table 3 and Table 4 for both sensor and sensorless modes of operation.

It can be observed that as load torque is increased, oscillations are reduced and torque ripples are reduced where as Flux Ripples are increased with load torque. It can be noticed that steady state performance is slightly better in case of MRAS where as transient response is slightly better using sensors.

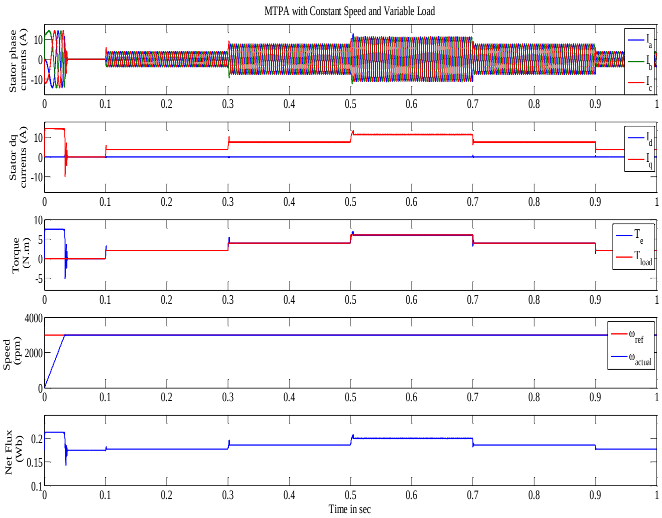

Fig 6. Responses of stator;direct,quadrature axis currents, torque, speed and flux for MTPA with Constant Speed and Variable Load using sensors

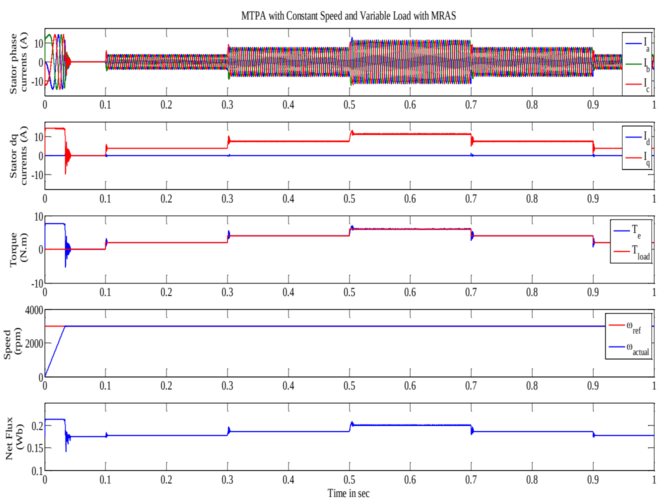

Fig 7. Responses of stator;direct,quadrature axis currents, torque, speed and flux waveforms for MTPA with Constant Speed and Variable Load using sensorless control (using MRAS)

Table 3: Drive Performance at Constant Speed 3000rpm Using Sensors

Time (sec)	T_L (N.m)	I_s (A)	I_d (A)	I_q (A)	Net Flux (Wb)	Torque Ripple (%)	Flux Ripple (%)
0.1	2	3.82		3.82	0.18	1.74	0.17
0.3	4	7.635		7.63	0.19	0.98	0.21
0.5	6	11.45	0	11.45	0.2	1.57	0.5
0.7	4	7.635		7.63	0.19	0.98	0.21
0.9	2	3.82		3.82	0.18	1.74	0.17

Table 4: Drive Performance at Constant Speed 3000rpm Using Sensorsless Control

Time (sec)	T_L (N.m)	I_s (A)	I_d (A)	I_q (A)	Net Flux (Wb)	Torque Ripple (%)	Flux Ripple (%)
0.1	2	3.82		3.82	0.18	1.49	0.17
0.3	4	7.632		7.632	0.19	0.87	0.21
0.5	6	11.5	0	11.55	0.2	1.60	0.5
0.7	4	7.635		7.635	0.19	0.87	0.21
0.9	2	3.82		3.82	0.18	1.47	0.17

6.3. Case III: Variable Speed and Variable Load condition

The dynamic performance of the drive is tested considering variable load torque and speeds. Fig.8 and Fig.9 shows the responses of stator current, direct axis current, quadrature axis current, electromagnetic torque, speed and flux waveforms for both sensor and sensorless modes and sensorless modes respectively.

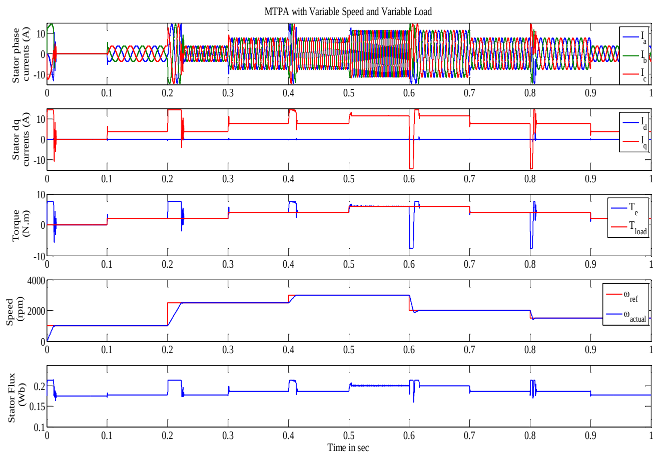

Fig 8. Responses of stator;direct,quadrature axis currents ,torque, speed and flux for MTPA with Variable Speed and Variable Load using sensors

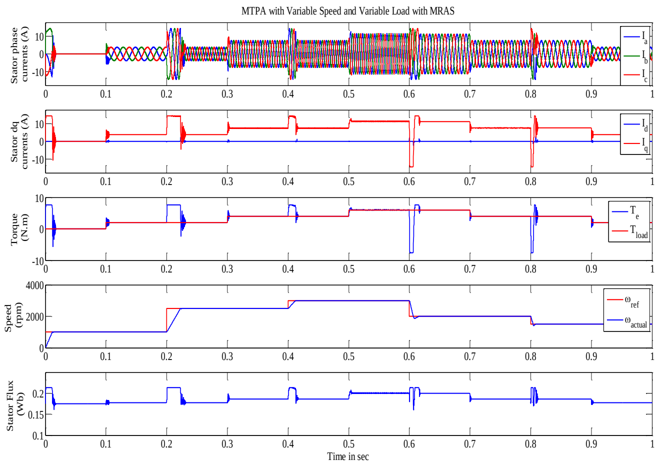

Fig 9. Responses of stator;direct,quadrature axis currents, torque, speed and flux for MTPA with Variable Speed and Variable Load using sensors (using MRAS)

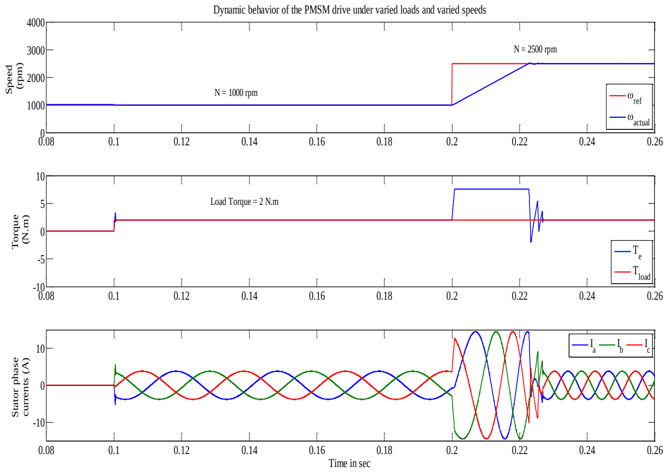

Fig 10. Dynamic behaviour of PMSM drive between 0.08 and 0.26 sec for Variable Loads and Variable Speeds

Since all the speeds are below rated speeds, d-axis current is maintained at near zero value. Load torque waveform shape and its magnitude are in proportion to quadrature axis current waveform. For a particular load torque, as and when speeds are varied, frequency of operation is varied.

Fig.10 shows the dynamics of the PMSM drive under variable loads and speeds. Torque Ripple and Flux Ripple percentages are calculated and are tabulated in Table 5 and Table 6 for both sensor and sensorless modes respectively.

For a particular load torque, it can be observed that as speed is increased torque ripple percentages and flux ripple percentages have increased. From the waveforms and ripple percentages it can be noticed that a near similar performance is seen in both sensor and sensorless modes. The parameters of PMSM drive used in this work are given in Table 7.

Table 5: Drive Performance at Variable Load and Speed Using Sensors

Time (sec)	Speed (rpm)	Load (N.m)	I_s (A)	I_d (A)	I_q (A)	Net Flux (Wb)	Torque Ripple (%)	Flux Ripple (%)
0.1	1000	2	3.8		3.8	0.18	0.7	0.06
0.2	2500	2	3.8		3.8	0.18	1.28	0.11
0.3		4	7.6		7.6	0.19	0.73	0.11
0.4	3000	4	7.6		7.6	0.19	0.88	0.21
0.5		6	11.4	0	11.4	0.2	1.5	0.45
0.6	2000	6	11.4		11.4	0.2	0.43	0.15
0.7		4	7.6		7.6	0.19	0.63	0.11
0.8	1500	4	7.6		7.6	0.19	0.48	0.05
0.9		2	3.8		3.8	0.18	0.84	0.06

Table 6: Drive Performance at Variable Load and Speed Using Sensorsless Control

Time (sec)	Speed (rpm)	Load (N.m)	I_s (A)	I_d (A)	I_q (A)	Net Flux (Wb)	Torque Ripple (%)	Flux Ripple (%)
0.1	1000	2	3.8		3.8	0.18	0.65	0.06
0.2	2500	2	3.8		3.8	0.18	1.2	0.11
0.3		4	7.6		7.6	0.19	0.68	0.11
0.4	3000	4	7.6		7.6	0.19	0.83	0.16
0.5		6	11.4	0	11.4	0.2	1.66	0.45
0.6	2000	6	11.4		11.4	0.2	0.42	0.15
0.7		4	7.6		7.6	0.19	0.55	0.11
0.8	1500	4	7.6		7.6	0.19	0.49	0.05
0.9		2	3.8		3.8	0.18	0.82	0.11

Table 7: Parameters of PMSM

Parameters	Values
Power Rating	2kW
Stator resistance (R_s)	2.8750Ω
Inductance d-axis (L_d)	0.0085H
Inductance q-axis (L_q)	0.0085H
Dc voltage (V_{dc})	160V
Rotor flux (λ)	0.175Wb
Moment of inertia (J)	0.0008kgm^2
Friction (B)	0.001Nm/rad
Poles (P)	4
Load Torque (T_L)	6 N-m

7. CONCLUSION

Rotor speed and position are estimated using MRAS technique in this work. Different operating conditions are applied at below rated speeds and the drive performance is validated in sensor and sensorless modes. From the waveform quality and torque ripple percentages, it is noticed that a similar performance is observed in both sensor and sensorless modes. Results of the proposed sensorless control system have demonstrated its effectiveness and fast dynamic response. It can be concluded that FOC in sensorless mode appears to more viable approach since it reduces cost, weight, size, complexity and increases reliability and robustness of the drive. This work can be extended for above base speeds using Flux Weakening technique in both sensor and sensorless modes thus covering wide speed ranges.

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