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FIELD ORIENTED CONTROL OF PMSM FED ELECTRIC VEHICLE

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ABSTRACT

The present research is indicating that the Permanent magnet motor drive could become serious competitor to the induction motor drive for servo application. Further, with the evolution of permanent magnet materials and control technology, the Permanent Magnet Synchronous Motor (PMSM) has become a pronounced choice for low and mid power applications such as computer peripheral equipments, robotics, adjustable speed drives and electric vehicles due to its special features like high power density, high torque/inertia ratio, high operating efficiency, variable speed operation, reliability, and low cost etc. However, the main disadvantage of PMSM is the non-uniform variance in the developed torque. Vector controlled PMSM drive provides better dynamic response and lesser torque ripples. This paper proposes a control scheme for a PMSM drive driven by Field Oriented Control (FOC). The proposed scheme is developed in MATLAB/SIMULINK environment. Simulation results are generated for testing the performance validity of the control law.

Keywords: Electric vehicle, PMSM, PWM, FOC, Vector Control.

1. INTRODUCTION

The Permanent Magnet Synchronous motor (PMSM) is a rotating electrical machine where the stator produces a sinusoidal flux density distribution in the air gap and the rotor has permanent magnets. From the last three decades AC machine drives are becoming more and more popular, especially Induction Motor Drives (IMD) and Permanent Magnet Synchronous Motor (PMSM), but with some special features, the PMSM drives are ready to meet sophisticated requirements such as fast dynamic response, high power factor, and wide operating speed range like high performance applications, as a result, a gradual gain in the use of PMSM drives will surely be witnessed in the future market in low and mid power applications [1] . Now in a permanent magnet synchronous machine, the dc field winding of the rotor is replaced by a permanent magnet to produce the air-gap magnetic field. Having the magnets on the rotor, some electrical losses due to field winding of the machine get reduced and the absence of the field losses improves the thermal characteristics of the PM machines hence its efficiency. Also lack of mechanical components such as brushes and slip rings makes the motor lighter, high power to weight ratio which assure a higher efficiency and reliability. With the advantages described above, permanent magnet synchronous generator is an attractive solution for wind turbine applications also. Like always, PM machines also have some disadvantages: at high temperature, the magnet gets demagnetized, difficulties to manufacture and high cost of PM material. As the demand for more environmental-friendly cars continues to grow, originating from both individual customers, as well as driven by governmental means, the failure of EVs has set the stage for the hybrid electric vehicle (HEV). In an HEV, the internal combustion engine is combined with electric propulsion. This provides several possible advantages, at the cost of increased complexity. The main advantages are increased range, the potential to operate the internal combustion engines at optimal (maximization of fuel economy, minimized emissions or a compromise between both) operating points and the use of regenerative braking. During regenerative braking, the energy used to slow or halt the vehicle is converted into electricity, which can charge the built-in battery, rather than wasting it as heat.

The performance of these motors in drive systems depend up on the motor control and method of control in power converter. The method of motor control is very important in the drive system. This is because the operation of the PMSM under effect of scalar control is suffered from complicated coupling nonlinear dynamic performance. This problem can be solved by field oriented control (FOC). PMSM with FOC emulates the separately excited DC motor. The control of an ac motor in field co-ordinates (also known as field oriented control or transvektor control) as proposed by Blaschke[2] for an induction machine and later by Bayer et al. [3] for a synchronous machine, leads to a decoupling between the flux and the torque resulting in a good dynamic torque and speed response [4] . In this method of control, the stator current can be decupled into flux and torque current components. They can be controlled separately. Vector control (or Field Oriented Control) principle makes the analysis and control of Permanent Magnet Synchronous Motor (PMSM) drives system simpler and provides better dynamic response. It is also widely applied in many areas where servo- like high performance plays a secondary role to reliability and energy savings. This paper presents the field oriented vector control scheme for permanent magnet synchronous motor (PMSM) drives, which regulates the speed of the PMSM. The performance of the motor suffers from uncertainties, parameters variation, and harmonics in both motor and inverter. They lead to problems in torque and oscillations in the speed come out as the secondary problem from the torque problem. To solve this problem, the torque must be studied.

The motor torque is a sum of: 1) Mutual torque, due to the interaction of the rotor field and stator currents; 2) Reluctance torque, due to rotor saliency; 3) Cogging torque, due to the existence of stator slots. These torques contain harmonics which lead to torque ripples. The mutual torque and reluctance torque have harmonics if the stator flux or rotor magnets are non- sinusoidal. The reluctance torque is exists only if the inductance is a function in the rotor position. The cogging torque arises due to geometry and slots in the PMSM. The machine design and control technique are used to reduce the torque ripple. The first method is complicated and high cost so the other method is preferable. Proportional integrator controller (PI), it is the most common controllers used in a wide range in the industrial applications. The popularity of PI control can be attributed to its simplicity. Due to its fixed proportional gain and integral time constant, the performance of the PI controllers are affected by parameter variations, load disturbances and speed variation. These problems can be overcome by the Fuzzy logic controller, which do not require any mathematical model and is based on the linguistic rules obtained from the experience of the system operator. SPWM and SVPWM can be used for effective switching of the inverter and the proposed system can be simulated using MATLAB/ Simulink environment.

2. MODELLING OF PMSM

The mathematical model of a PMSM is similar to that of wound rotor synchronous motor. The rotor winding of synchronous motor is replaced with high resistivity permanent magnet material, hence induced current in the rotor are negligible. The rotor types of PMSM are shown in Fig. 1. The permanent magnets on the rotor are shaped in such a way as to produce sinusoidal back EMF in stator windings. PMSM is an important category of the electric machines, in which the rotor magnetization is created by permanent magnets attached to the rotor. Many mathematical models have been proposed for different applications, such as the abc-model and the two axis dq-model. Due to the simplicity of the two axis dq-model, it becomes the most widely used model in PMSM engineering controller design. The dq-model offers significant convenience for control system design by transforming stationary symmetrical AC variables to DC ones in a rotating reference frame. Based on the d-q reference frame theory. The mathematical model of PMSM can be expressed by considering the following assumptions. The two axes PMSM stator windings can be considered to have equal turn per phase. The rotor flux can be assumed to be concentrated along the d axis while there is zero flux along the q axis, an assumption similarly made in the derivation of indirect vector controlled induction motor drives. The rotor flux is assumed to be constant at a given operating point. There is no need to include the rotor voltage equation as in the induction motor since there is no external source connected to the rotor magnet and variation in the rotor flux with respect to time is negligible. The stator equations of the induction machine in the rotor reference frames using flux linkages are taken to derive the model of the PMSM. The rotor reference frame is chosen because the position of the rotor magnets determine independently of the stator voltages and currents, the instantaneous induced emfs and subsequently the stator currents and torque of the machine..

The stator flux linkage vector ψs and rotor flux linkage ψf of PMSM can be drawn in the rotor flux (dq), stator flux (xy), and stationary (DQ) frames as shown in figure 1.

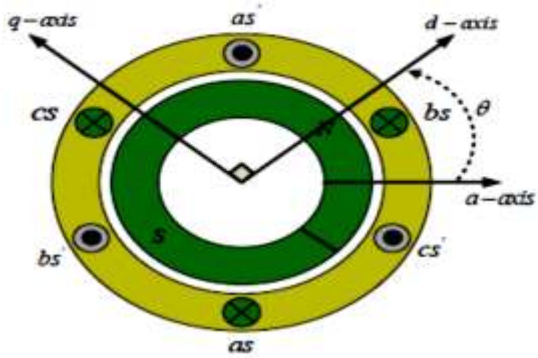

Fig.1. Two pole three phase surface mounted PMSM.

hen rotor references frame are considered, it means the equivalent q & d axis stator windings are transformed to the reference frames that are revolving at rotor speed. The consequences is that there is zero speed differential between the rotor and stator magnetic fields and the stator q and d axis windings have a fixed phase relationship with the rotor magnet axis which is the d axis in the modeling. The angle between the stator and rotor flux linkage δ is the load angle when the stator resistance is neglected. In the steady state, δ is constant corresponding to a load torque and both stator and rotor flux rotate at synchronous speed.

The stator flux reference frame in D axis is in phase with stator flux linkage space vector Ψs. Q axis (of SRF) leads 900 to D axis in CCW direction.

θs = rotational angle of stator flux vector, $\theta_s = \frac{d\theta_r}{dt}$

θr = rotational electric angle of rotor, $\theta_s = \theta_r + \delta$

Stator flux linkage is given by

$\Psi_s = L_s I_s + \Psi_{af} e^{j\theta r}$ (1)

Where Ls is stator self inductance and Ψ_{af} is the rotor permanent magnet flux linkage. The stator voltage equation in rotor reference frame (dq reference frame) are given as

$V_d = R_d I_d + \frac{d\Psi_d}{dt} - \omega_r \Psi_q$ (1a)

$V_q = R_q I_q + \frac{d\Psi_q}{dt} + \omega_r \Psi_d$ (1b)

Where R_d & R_q are the direct and quadrature axis winding resistances which are equal & be referred to as R_s in the stator resistance.

To compute the stator flux linkage in q & d axes, the current in stator & rotor are required. The permanent magnet excitation can be modeled as a constant current source ,if the rotor flux along d axes . So the d axes rotor current is i_f. The q axis current in rotor is zero,because there is no flux along this axis in rotor,by assumption. Then the flux linkage are written

$\Psi_q = L_q i_q$ (2)

$\Psi_d = L_d i_d + \Psi_f$ (3)

Ψ_f is the flux through stator winding due to permanent magnets

$$\Psi_f = L_m i_f$$

3. EQUIVALENT CIRCUIT OF PMSM

From the d-q modeling of the motor using the stator voltage equations the equivalent circuit of the motor can be derived as shown in fig.2 . Assuming rotor d axis flux from the permanent magnet is represented by a constant current source as described in the following equation ψf = LmIf . Figure shows the equivalent circuit derived from eq. 4]. Te =3/2 P (ψdId + (Ld - Lq)IqId) (4)

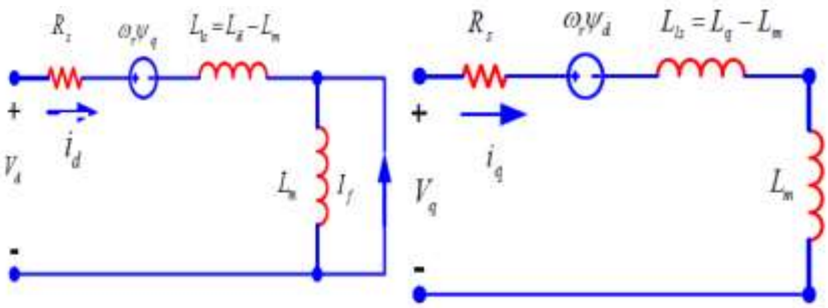

Fig.2 Equivalent Circuit of PMSM.

Where Lm is the mutual inductance between the stator winding and rotor magnets. Substituting these flux linkages into the stator voltage equations gives the stator equations.

$vq = RsIq + \omega_r(LdId + \Psi f) + \rho LqIq$ (5)

$Vd = RsId + \omega_r LqIq + \rho Rd(LdId + \Psi f) + Ldid$ (6)

Where Vd and Vq are d-q axis stator voltages, id and iq are d-q axis stator currents, Ld and Lq are d-q axis inductances. Rs is stator winding resistance per phase, Ψd, Ψq are stator flux linkage in d-q axis & ωr is rotor speed in (rad/sec) electrical. Arranging the above equation in matrix form

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_q + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_d + \rho L_d \end{bmatrix} + \begin{bmatrix} \omega_r L_m i_f \\ \rho \Psi_f \end{bmatrix} \quad (7)$$

The developed torque motor is being given by (8)

$Te = \frac{3}{2} P(\Psi dId - \Psi qIq)$ (8)

which upon substitution of the flux linkages in terms of the inductances and current yields

Te=3/2P(ψdId+(Ld-Lq)IqId) (9)

Where P= No. of pole pair = p/2, and p= Total No. of poles Based on theory of dynamics the motion equation of PMSM is given by

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$$T_e = T_L + B\omega_r + J\frac{d\omega_m}{dt} \qquad (10)$$

Where TL is load torque, J is moment of inertia, B (viscous friction) is damping coefficient.

The developed electromagnetic torque is given by

$$T_e = \frac{3}{2}\,P\left[\Psi_d i_q - \Psi_q i_d\right] \qquad (11)$$

ω_m is the motor mechanical speed. Solving for the rotor mechanical speed from the above equation

$$\omega_m = \int \frac{(T_e + T_L + B\omega_r)dt}{\tau}$$

And $\omega_m = \omega_r \frac{2}{p}$ Where ω_r is the rotor electrical speed.

4. SPEED CONTROL OF PMSM

The Field Orientated Control (FOC) consists of controlling the stator currents represented by a vector. This control is based on projections which transform a three phase time and speed dependent system into a two co-ordinate (d and q co-ordinates) time invariant system. These projections lead to a structure similar to that of a DC machine control. Field orientated controlled machines need two constants as input references: the torque component (aligned with the q co-ordinate) and the flux component (aligned with d co-ordinate). As FOC is simply based on projections the control structure handles instantaneous electrical quantities. This makes the control accurate in every working operation (steady state and transient) and independent of the limited bandwidth mathematical model. In order to achieve better dynamic performance, a more complex control scheme needs to be applied, to control the PM motor. With the mathematical processing power offered by the microcontrollers, we can implement advanced control strategies, which use mathematical transformations in order to decouple the torque generation and the magnetization functions in PM motors. Such de-coupled torque and magnetization control is commonly called rotor flux oriented control, or simply Field Oriented Control (FOC), three phase currents are measured. The measured currents are transformed using the Clarke transformation into a stationary frame (α-β) $I_{s\alpha}$ and $I_{s\beta}$. These two currents then are transformed into rotating frame (d-q) I_{sd} and I_{sq}. The PI controllers compare the command values with the measured values to judge the operation condition.

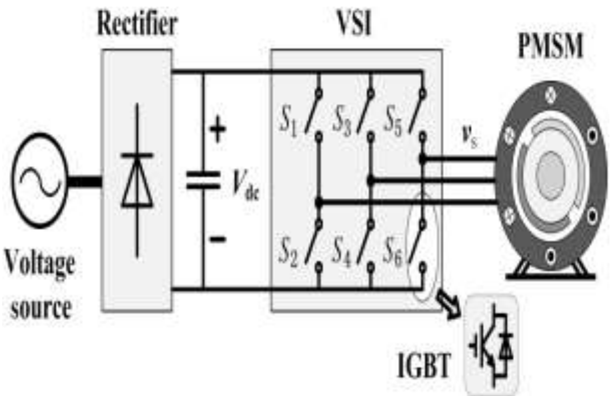

Fig.3 Speed Control of PMSM

The outputs of the controllers are transformed from a rotating frame to stationary frame by using the Park transformation. The commanded signals of the vector are sent to the pulse width modulation (PWM) block.

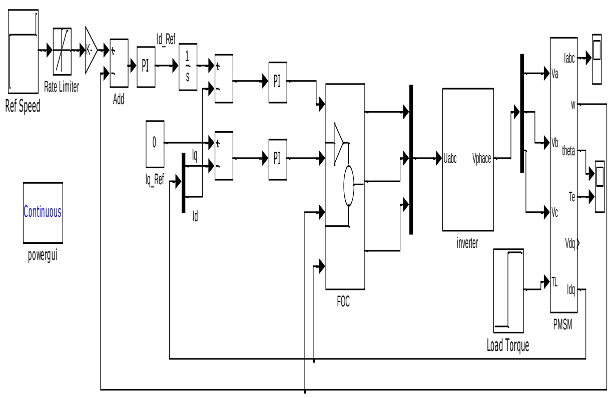

Fig. 4 Field oriented control of PMSM scheme.

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The performance of the FOC block diagram can be summarized in the following steps

1. The stator currents are measured as well as the rotor angle.
2. The stator currents are converted into a two-axis reference frame with the Clark Transformation.
3. The αβ currents are converted into a rotor reference frame using Park Transformation. This dq values are invariant in steady-state conditions.
4. With the speed regulator, a quadrature-axis current reference is obtained (the direct-axis reference is zero for operation below rated speed). The d-current controls the air gap flux, the q-current control the torque production.
5. The current error signals are used in controllers to generate reference voltages for the inverter.
6. The voltage references are turned back into abc domain.
7. With these values are computed the PWM signals required for driving the inverter.

5. SIMULATION RESULTS AND DISCUSSION

To verify the operation of the proposed topology and the performance of the modulation techniques, a model is developed and simulated. Permanent magnet synchronous motors (PMSM) are widely used in low and medium power applications such as computer peripheral equipments, robotics, adjustable speed drives and electric vehicles. The growth in the market of PMSM motor drives has demanded the need of simulation tool capable of handling motor drive simulations. Simulations have helped the process of developing new systems including motor drives, by reducing cost and time. Simulation tools have the capabilities of performing dynamic simulations of motor drives in a visual environment so as to facilitate the development of new systems .The model of speed control of permanent magnet synchronous motor (PMSM) drive are developed in MATLAB environment with simulink & PSB tool boxes to simulate the behaviour of drive with PI controller. In this test system, the reference speed is increased from ωr =0 to 1500 rpm at 0.5, 1500 to 1650 rpm at t=1 sec., sudden speed reversal at t=2 and again at t=2.5 sec. The torque is also from TL= 5 Nm to 10 Nm at t = 2.5 seconds. The torque is maintained constant while the PMSM drive is subjected to step increase in speed reference. It is clear from fig- 6 that the motor oscillates for a few cycle; when speed reversal takes place. Again there is a slight dip in speed of machine when load torque TL is changed from 5 Nm to 10 Nm. At this instant the d axis current and q axis current of the machine also increases to match with the increase in load torque demand.

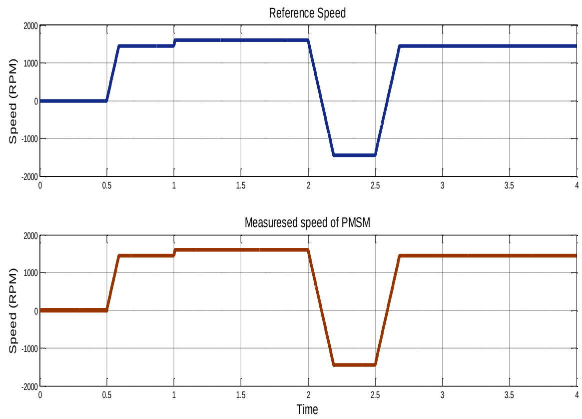

Fig. 5 Reference and Measured speed of PMSM drive

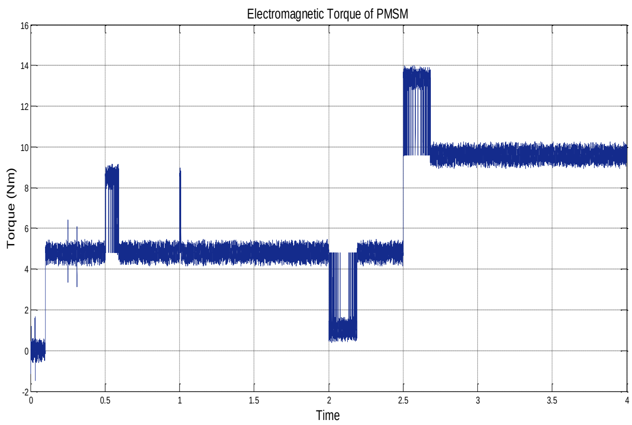

Fig. 6. Electromagnetic torque of PMSM drive

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The motor torque ripple is larger when the PMSM Drive is either started or when there is a change in reference speed, as viewed from fig 5. This is because electromechanical time constant is much larger then electromagnetic time constant, instantaneous rate of change of stator flux linkage is larger than that of rotor flux linkage. At the time of perturbation in speed change, system doesn't reach equilibrium. When the actual motor torque is less than the given value, the angle between the stator & rotor flux linkage increased, that leads the torque growing fast, and vies reverse. This is the reason why the motor torque ripple is larger when the motor is subjected to change in speed reference and also at the time of starting of PMSM drive.

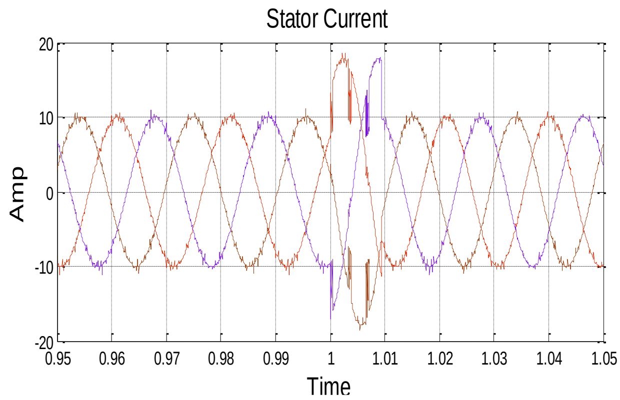

Fig. 7 Zoomed view of stator current above rated speed

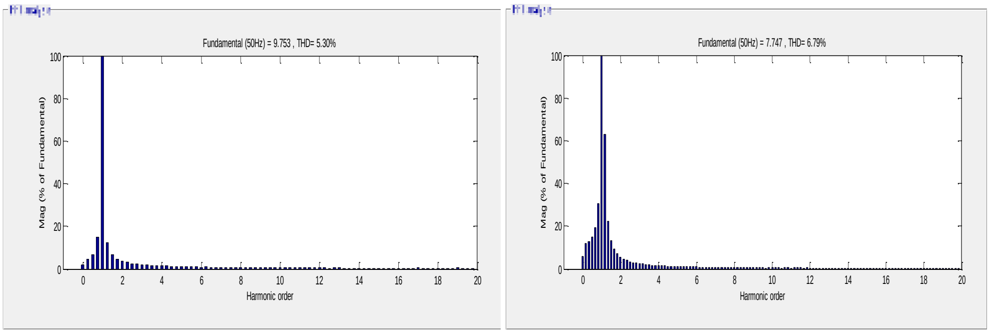

Fig. 8 THD of stator current for starting of PMSM drive at rated speed, above rated speed

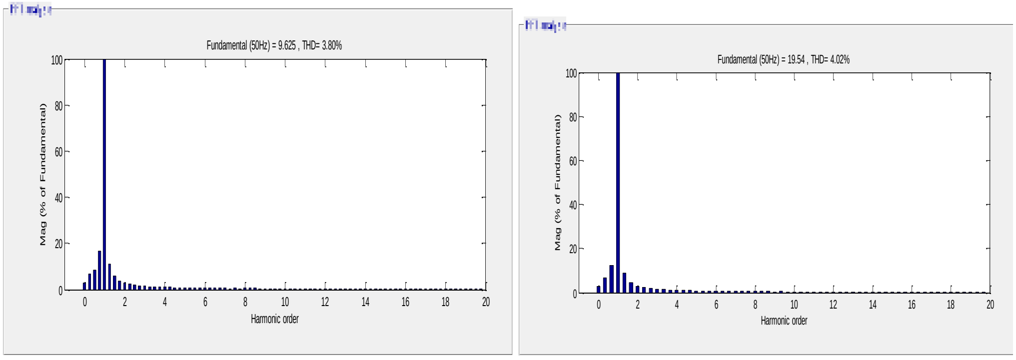

Fig. 9 THD of stator current for starting of PMSM drive under speed reversal, increase in torque

6. CONCLUSION

In this paper, closed loop vector control of PMSM drive system has been proposed. The PI speed controller was used in speed loop, and it helped to improve the system performance. Simulation results demonstrated the higher efficiency and better dynamic response of the proposed method as compared with traditional method over a wide range of load variation. The simulation results also showed high efficiency and high dynamic performance of PMSM drive system.

7. REFERENCES

[1] M. N. Uddin, T. S. Radwan, and M. Azizur Rahman, "Fuzzy-Logic-Controller-Based Cost-Effective Four-Switch Three-Phase Inverter-Fed IPM Synchronous Motor Drive System", IEEE trans. on Industry applications, vol. 42, no. 1, 2006, pp. 21-30.

[2] Sant and K. R. Rajagopal, "PM Synchronous Motor Speed Control Using Hybrid Fuzzy-PI With Novel Switching Functions", IEEE trans. on magnetics, vol. 45, no. 10, Oct. 2009, pp. 4672-4675.

[3] R. Nalepa, and T.-Kowalska, “Optimum Trajectory Control of the Current Vector of a Nonsalient-Pole PMSM in the Field-Weakening Region, IEEE Trans. On Industrial electronics, vol. 59, no. 7, July 2012, pp. 2867-2876.

[4] Sant, K. R. Rajagopal, and N. Seth, “Permanent Magnet Synchronous Motor Drive Using Hybrid PI Speed Controller With Inherent and Noninherent Switching Functions”, IEEE trans. on Magnetics, vol. 47, no. 10, october 2011, pp.4088-4091.

[5] Gaeta, G. Scelba, and A. Consoli, “Sensorless Vector Control of PM Synchronous Motors During Single-Phase Open-Circuit Faulted Condition”, IEEE trans, on industry applications, vol. 48, no. 6, Dec. 2012, pp. 1968-1979

[6] T. Ishikawa, Y. Seki, and N. Kurita , “Analysis for Fault Detection of Vector-Controlled Permanent Magnet Synchronous Motor With Permanent Magnet Defect”, IEEE trans. on Magnetics, vol. 49, no. 5, may 2013, pp.2331-2334.

[7] B.V.Lakshma Reddy, U.Anjaiah & T.Srinivasa Rao, “A Closed Loop Speed Control of PMSM Drive Using Fuzzy Logic Controller”, Imperial Journal of Interdisciplinary Research Vol-2, Issue-6, 2016.

[8] A.Iqbal, H. Rub and H. Nounou, “Adaptive fuzzy logic-controlled surface mount permanent magnet synchronous motor drive”, Systems Science & Control Engineering, 2014, Vol. 2, 465–475.

[9] L. Mathew and V. Pandey, “Design and development of fuzzy logic controller to control the speed of permanent magnet synchronous motor”, Journal of Electrical and Electronics Engineering Research Vol. 3(3), pp. 52-61, March 2011

[10] M. Chakraborty, “ Comparative Analysis of Speed Control of PMSM using PI-Controller and Fuzzy Controller”, International Journal of Scientific & Engineering Research, Volume 4, Issue 7, July-2013, pp. 103-108.

[11] M. Dogan, M. Dursun, “Application of speed control of permanent magnet synchronous machine with PID and Fuzzy Logic Controller”, Energy Education Science and Technology Part A: Energy Science and Research 2012 Volume (issues) 28(2): 931-936

[12] Matthew LiamDe Klerk∗, Akshay KumarSaha, “ Performance analysis of DTC-SVM in a complete traction motor control mechanism for a battery electric vehicle, Heliyon 8 (2022) pp 1-16, https://doi.org/10.1016/j.heliyon.2022.e09265

[13] Chiranjit Sain, Pabitra Kumar Biswas, Priya Ranjan Satpathy, Thanikanti Sudhakar Babu And Hassan Haes Alhelou, “Self-Controlled PMSM Drive Employed in Light Electric Vehicle-Dynamic Strategy and Performance Optimization” VOLUME 9, 2021, IEEE Access, pp. 57967-57975.

[14] Zhikun Wang, Tze Wood Ching, Shaojia Huang, Hongtao Wang, and Tao Xu, “Challenges Faced by EV Motors and Their Solutions”, VOLUME 9, 2021, IEEE Access, pp. 5528-5249