IJAREEIE

e-ISSN: 2278-8875
p-ISSN: 2320-3765

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

Volume 10, Issue 2, February 2021

INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA

Impact Factor: 7.122

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (IJAREEIE)

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 7.122|

||Volume 10, Issue 2, February 2021||

DOI:10.15662/IJAREEIE.2021.1002008

Speed Control of Electric Vehicle with Fuzzy Logic

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ABSTRACT: Permanent Magnetic Synchronous Motor (PMSM) has been increasingly used in many high performance application like electric vehicles due to its advantages of high power density, high power factor and efficiency. This paper proposes a fuzzy logic based speed control of permanent magnet synchronous machines (PMSM) drive. Vector control techniques have made possible the application of PMSM motors for high performance applications where traditionally only dc drives were applied. PMSM torque control has traditionally been achieved using Field Oriented Control (FOC), using powerful simulation capabilities of MATLAB/ Simulink, the entire drive system is modelled using modular approach. The proposed fuzzy logic based speed controller is investigated under sudden change in load demand and frequent changes in speed including sudden speed reversals.

KEYWORDS: PMSM, PWM, Fuzzy Logic Controller, Vector Control.

I. INTRODUCTION

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 PMSM is very much used for variable speed drives due to high torque to weight ratio, high power to weight ratio, high power factor and high efficiency. The speed control of PMSM (Permanent Magnet Synchronous Motor) is quiet difficult because of the non-linear coupling of winding currents and rotor speed. The paramount requirement of the high performance drive is to have fast and accurate speed response without any effect of load disturbance. In Recent years, researchers and industries have been paying attention to permanent magnet synchronous machines due to simple structure as compared with other machines. High performance electrical drives using PMSM require the knowledge of the rotor position to implement the field oriented control. Mechanical sensors can provide the information for the rotor position; however they increase the cost and decrease the reliability of the drive. Besides, mechanical sensors are susceptible to fail in harmful environment conditions [1].

Field oriented control is a control mechanism to flexibly drive synchronous and induction motor. It allows decoupling control of torque and speed of AC motors similar to separately excited DC motors. Since in DC motor, armature current which directly control the torque and field current in the rotor which produce magnetizing flux are independently accessible and armature mmf and rotor flux held orthogonally with respect to each other through mechanical commutation system such as brushes and commutators. But in case of AC motors (Synchronous and Induction motor), spatial angle between rotating stator field and rotor flux changes with the load which causes oscillatory response. FOC emulate the DC conditions in AC motor structure by monitoring the rotor field position and orient the stator field accordingly so that angle between both of the fields can be maintain at 90o. In this way maximum torque condition can be achieved while independently controlling rotor speed [2–3]. FOC require a position sensor for constantly monitoring the rotor position, hence rotor flux position too. Stator field is oriented through varying phase and magnitude of three phase ac quantities. Hence it is also referred as 'vector control' [4-7]

II. MODELLING OF PMSM

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 & 2

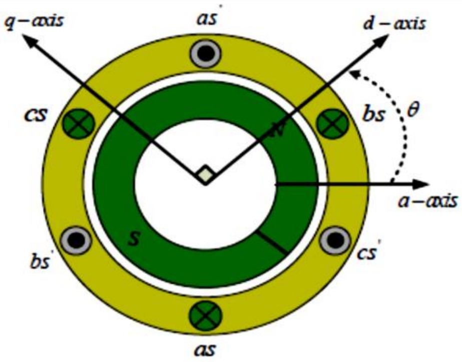


Fig.1. Two pole three phase surface mounted PMSM.

When 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 ψaf ix the rotor permanent magnet flux linkage. The stator voltage equation in rotor reference frame (dq reference frame) are given as

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

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

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

$$\Psi_f = L_m i_f$$

III. 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 ᴪf = LmIf . Figure shows the equivalent circuit derived from eq. 4].

$$Te = 3/2P(\Psi dId+(Ld-Lq)IqId) \qquad (4)$$

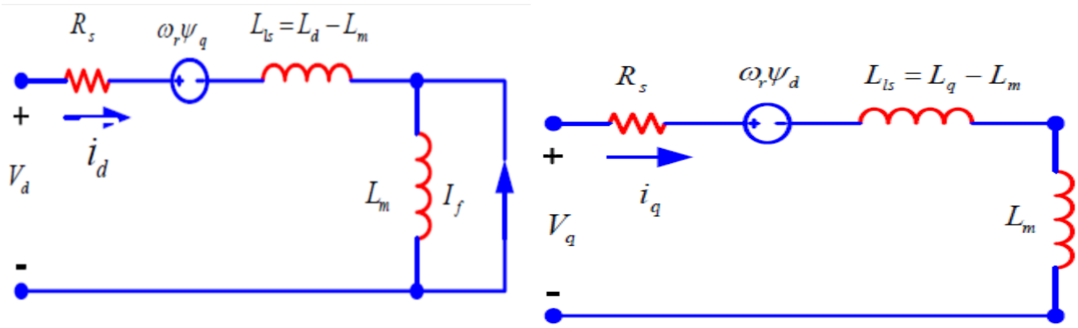


Fig.2 Equivalent Circuit of PMSM

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.

$$v_q = R_s I_q + \omega_r (L_d I_d + \Psi_f) + \rho L_q I_q \qquad (5)$$

$$V_d = R_s I_d + \omega_r L_q I_q + \rho R_d (L_d I_d + \Psi_f) + L_d i_d \qquad (6)$$

Where V_d and V_q are d-q axis stator voltages, id and iq are d-q axis stator currents, L_d and L_q are d-q axis inductances. R_s 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

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

The developed torque motor is being given by (8)

$$Te = \frac{3}{2} P (\Psi_d I_d - \Psi_q I_q) \qquad (8)$$

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

$$T_e = 3/2P(\Psi_d I_d + (L_d - L_q) I_q I_d) \qquad (9)$$

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

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

Where T_L 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.

IV. SPEED CONTROL OF PMSM FED ELECTRIC VEHICLE

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.

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.

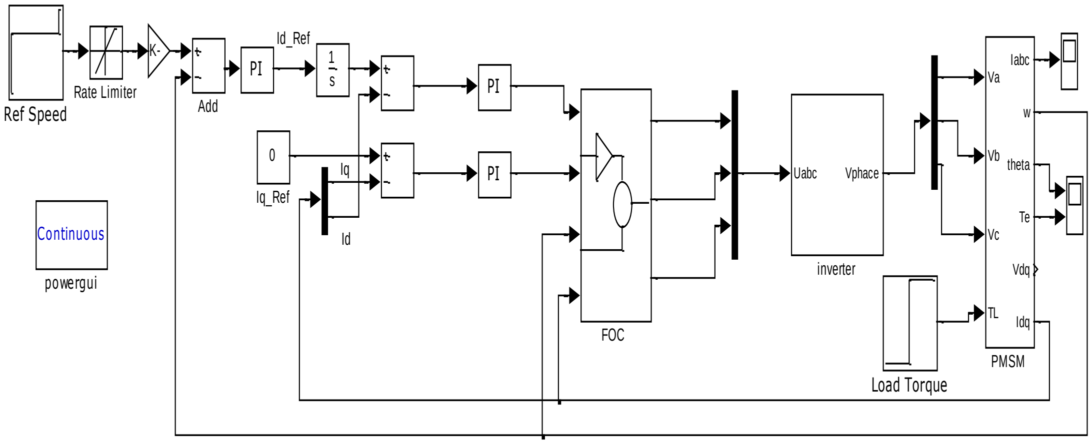


Fig. 3 Field oriented control of Electric vehicle.

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.

V. FUZZY LOGIC CONTROL

Mostly, a Proportional-integral (PI) controller is used as speed controller of Electric vehicledespite the presence of many nonlinear techniques. A PI controller is more prone to effects of Load disturbances, speed changes, and parameter variation if its gains are not tuned continuously. The evolution of artificial intelligence techniques like Fuzzy Logic Controller (FLC) provides improved speed control performance of drive. Amidst various intelligent controllers we find FLC to be the simplest one and it is better than other controllers in terms of faster response

DOI:10.15662/IJAREEIE.2021.1002008

insensitivity towards load variation. To overcome the shortcomings of the PI controller, an FLC controller with 49 rules is designed for speed control of PMSM drive. The dynamic performance of the drive is quite improved by the Fuzzy Logic controller as compared to the PI controller. The use of linguistic variables and user defined rule base gives a major merit to incorporate human intelligence in the controllers.

The general control scheme of Electric vehicle using Fuzzy Logic controller is shown in Fig. 5. The control scheme involves closed loop control of speed and current. The three phase currents ia , iband ic are measured by the rotor circuit and are transformed to DC components i d and i q through Park's transformation. This current is then taken to the current feedback loop. The deviation between the speed reference and actual speed is regulated by FLC and thus the current reference of d, q axis i.e. i_{dref} and i_{qref} are generated. The current is regulated by individual flc controllers for DC components i.e. i_d and i_q . The regulated DC currents produce three phase stator current and thus voltages that are fed to the voltage source inverter which produces required Torque and speed

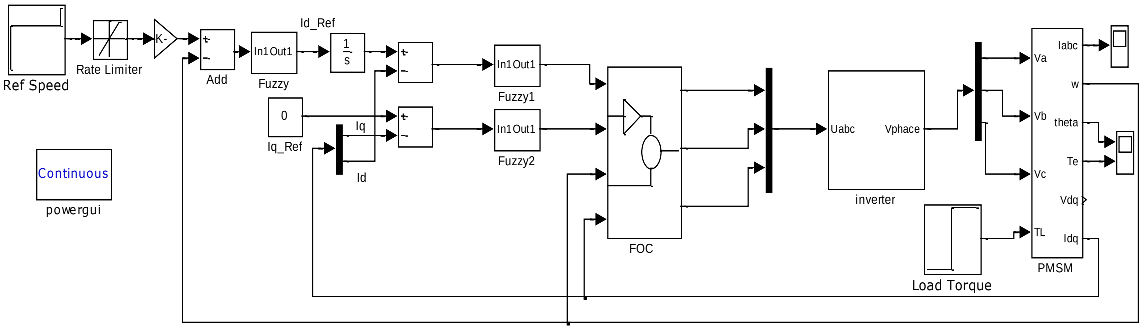


Fig.4. Basic control scheme of Electric Vehicle using FLC

In Fuzzy Logic Controller (FLC), speed error (ωe) and change in speed error (dw_e/dt) are considered as two fuzzy input variables. The FFC output is ΔIw. This output is summed or integrated to generate actual output If. Each of these two input variables are represented by a set of five membership functions as negative g (N), negative small (NS), zero (Z), positive small (PS), positive (P). All the membership functions are symmetrical about its positive and negative values. The change in output variable (ΔI_w) is represented by set of five membership functions from negative (N) to positive (P) membership functions. The triangular function is used in this system due to their better robustness. The most important part of the algorithm is to formulate the fuzzy rules or knowledge base. The IF –THEN weighted 25 rules are shown in table.1.

Sample the speed w and 'w_{reff}' and compute the speed error w_e (y) = w_{reff} (y) − w (y)

$cw_e = w_e (y) – w_e (y-1)$

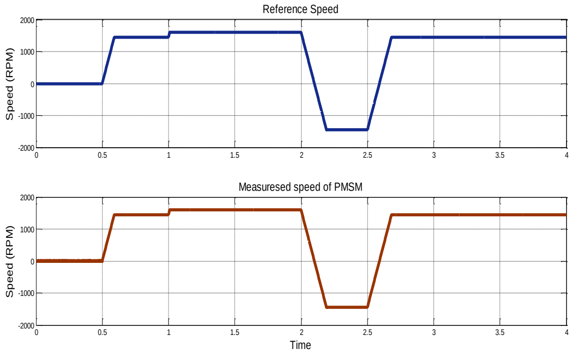
These we and cw_e are divided by scaling factor SF and SQ respectively to convert the signal in per unit values The amplitude of output of FLC is given as: $I_w(y) = I_w(y-1) + \Delta I_w$

Table I Fuzzy Control Rules

ERROR ⇩	CHANGE IN ERROR ⇨				
	N	NS	Z	PS	P
N	N	N	NS	Z	PS
NS	NS	NS	NS	Z	PS
Z	NS	NS	Z	PS	P
PS	NS	Z	PS	PS	P
P	N	NS	Z	PS	P

VI. SIMULATION RESULTS & 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 Electric vehicle 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 T_L 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.


Reference Speed

Measuresed speed of PMSM

Fig. 5 Measured speed of PMSM drive

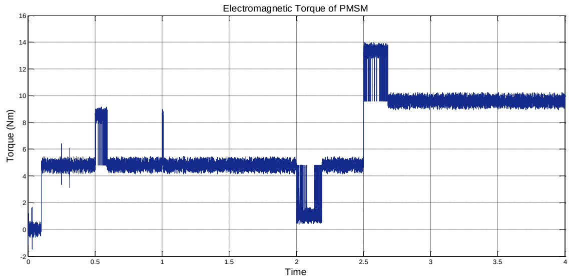

Electromagnetic Torque of PMSM

Fig. 6. Electromagnetic torque of PMSM drive

The motor torque ripple is larger when the Electric vehicle 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 versa. 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.

The figure 7 shows the three phase stator current of PMSM drive. The machine current changes with change in speed & load torque. It increases with increases in load torque so as to develop more electromagnetic torque to counter load torque demand.

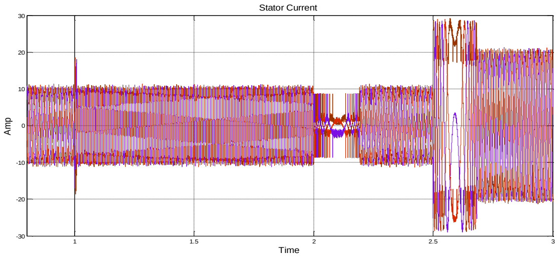

Stator Current

Fig. 7 Stator current of PMSM for change in speed

Fig. 8 & 9 shows the zoomed view of stator current during increase in speed above rated speed and during sudden speed reversal.

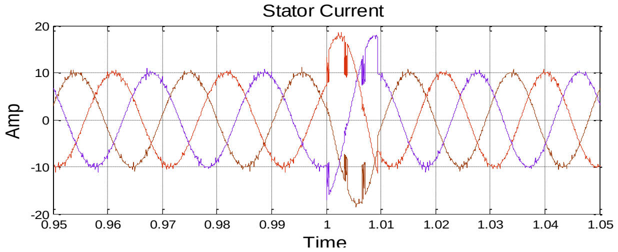


Fig. 8 Stator current above rated speed

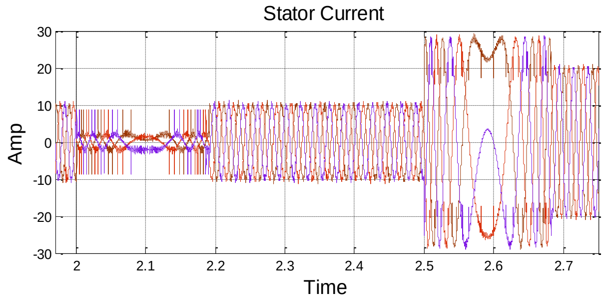


Fig.9 Stator current for speed reversal

Fig.10 and Fig. 11 shows the THD of stator current during sudden speed changes with PI controller.

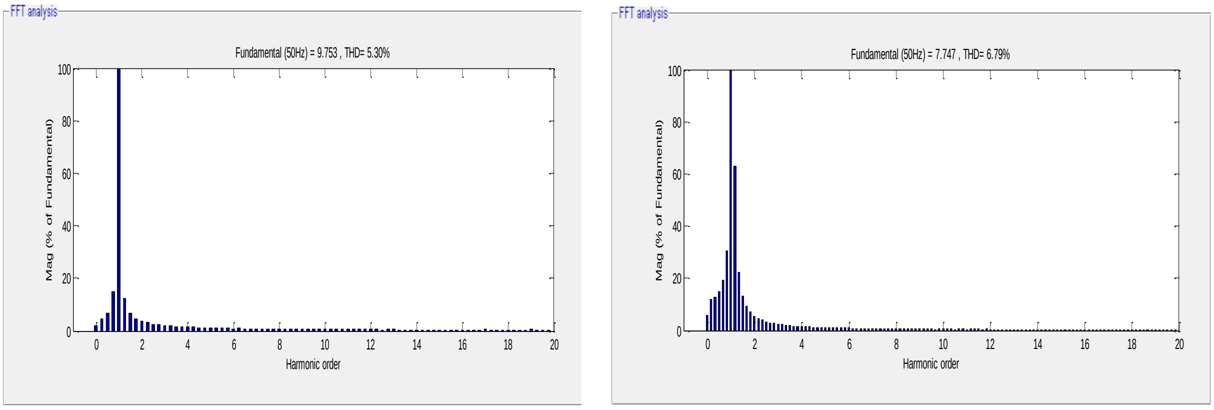


Fig.10 THD of stator current for starting of Electric vehicle at rated speed, above rated speed

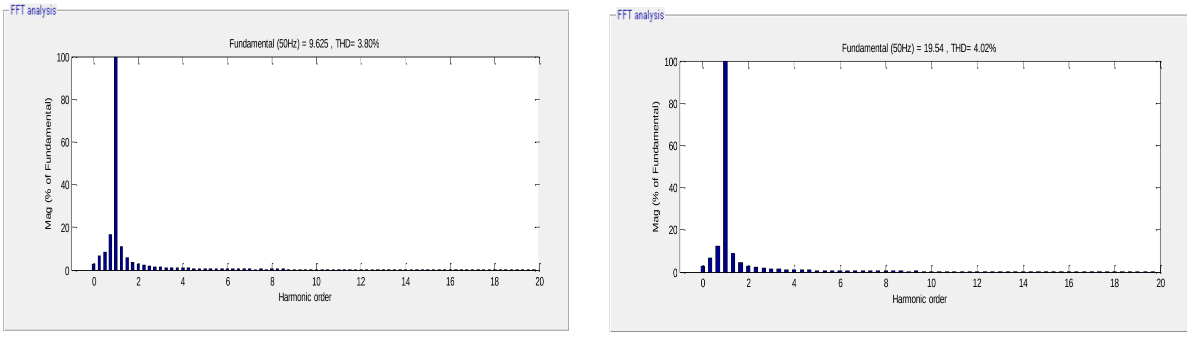


Fig.11 THD of stator current for starting of Electric vehicle under speed reversal, increase in torque

Fig. 12 shows the torque response of Electric vehicle with fuzzy control. It is observed that the torque ripples during sudden speed changes with fuzzy logic controller is comparatively small as compared with PI controller.

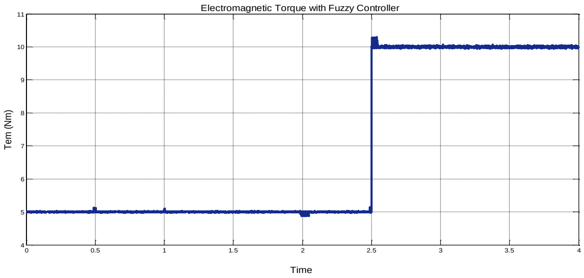


Fig. 12 Electromagnetic torque of Electric vehicle with fuzzy control

Fig.13 and Fig.14 shows the THD of stator current during sudden speed changes with Fuzzy logic controller.

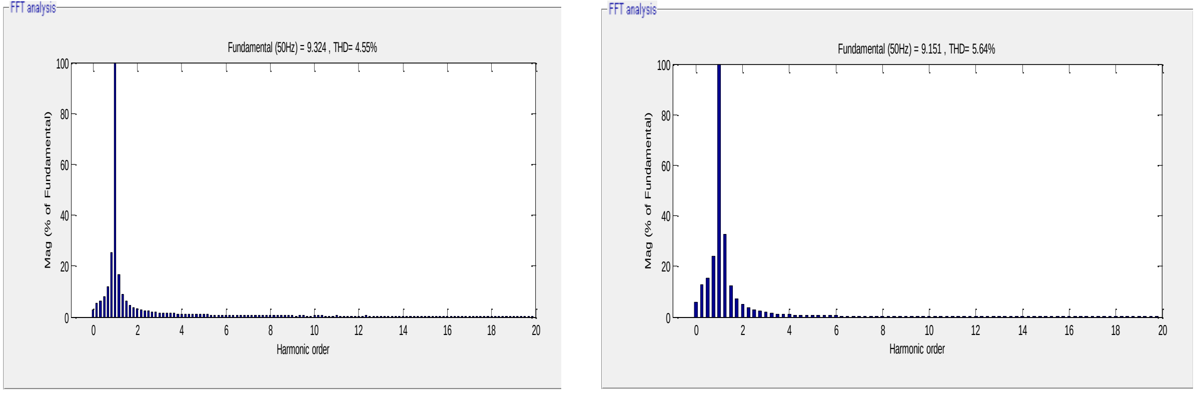


Fig. 13 THD of stator current for rated speed, above rated speed with Fuzzy logic controller.

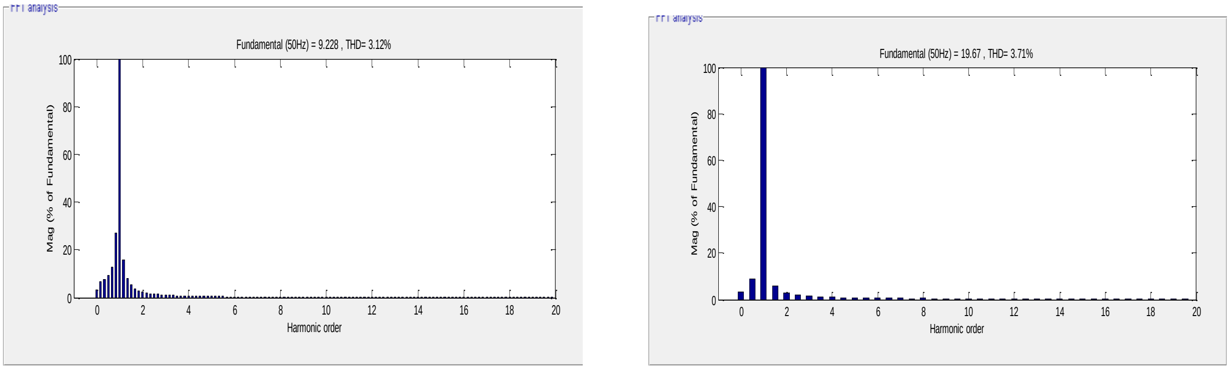


Fig. 14 THD of stator current for speed reversal, increase in torque with Fuzzy logic controller.

Table 1-summarizes the THD for PI and Fuzzy controlled PMSM drive. It is clear that by using fuzzy logic controller performance of the system is improved.

TABLE-1 Comparison of THD for PI and Fuzzy controlled Electric vehicle

THD of stator current	Fuzzy	PI
Rated speed	4.56	5.30
Above rated speed	5.64	6.79
Speed reversal	3.12	3.80
Increase in torque	3.71	4.02

VII. CONCLUSION

In this thesis, fuzzy logic speed controller based closed loop vector control of Electric vehicle system has been proposed. The fuzzy logic speed controller was used in speed loop, and it helped to improve the system performance. A performance comparison of the fuzzy control based Electric vehicle system and conventional PI controller based drive system is also provided in the simulation. 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 the proposed fuzzy control based Electric vehicle system.

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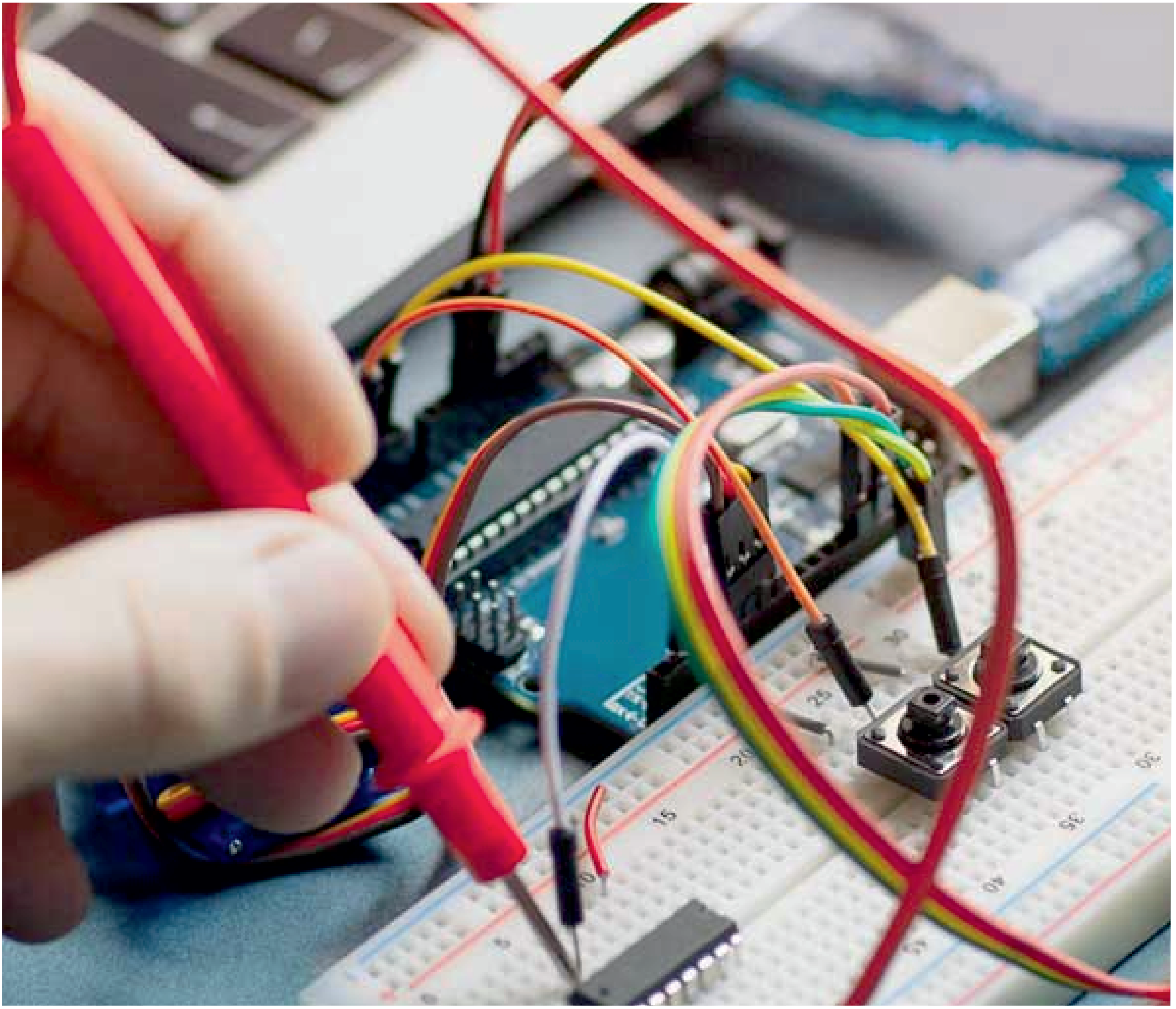

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