State Feedback Speed Control of Permanent Magnet Synchronous Motor for an Electric Vehicle

[1]Rumana Farheen.N, [2]Dr.S.G .Bharathi Dasan

[1]PG Scholar, [2]Associate Professor,
Department of EEE
Sri Venkateswara College of Engineering
Pennalur, Sripreumbudur 602117

***Abstract-* Electric Vehicle widely known for its environmental and mechanical efficiency. It requires smooth starting, braking and running operations. To meet these requirements the Electric Vehicle consists of one or more electric motors for various propulsion. The motors used in Electric Vehicle are DC motor, Universal motor and Induction motor. These motors have proved to have certain disadvantages like are poor speed control and high starting torque. To overcome such challenges the Permanent Magnet Synchronous Motor (PMSM) is suggested and it is widely used in motion control applications as they have dynamic property. A Controller is used to improve steady state and dynamic characteristics of a system. State feedback controller is suggested in this paper because it is superior to PID controller, as it permits us to place all roots of the characteristic equation at the desired locations. The aim of this project is to control speed of permanent magnet synchronous motor (PMSM) for an Electric Vehicle using state feedback controller (SFC). During designing process of SFC a state space representation of an augmented system is considered by using MATLAB**

Index Terms— Electric Vehicle; State Feedback controller; Permanent Magnet Synchronous Motor

I. INTRODUCTION

The big threat which the world faces is the Pollution and the consequences of it. Everyone is working towards a clear environment in various levels. Vehicles running on Fossil Fuel are the major contributions to this threat due to their harmful emssions.Electric Motor Vehicles has been designed to mitigate such harmful threats. So it's becoming popular for their Environmental and Mechanical efficiency.

Globally Vehicle Characteristics are Smooth Running, without halt Braking and Quick Starting. These Characteristics have also been achieved by Electric Vehicle motor drive by using accurate controller.

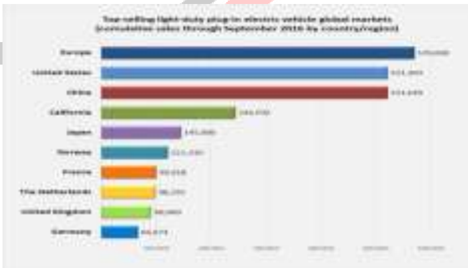

Figure 1 Worldwide scenario of EV usage

Figure 2 Per capita EV usage

Until September 2016, cumulative sales of highway legal light-duty plug-in electric vehicles by country were led by the United States and China, both with about 520,000 plug-in passenger cars sold. Japan is the world's third largest plug-in car market with about 145,000 plug-ins sold through September 2016. About 570,000 light-duty plug-in electric passenger cars have been registered in Europe up until September 2016, representing almost a third of global sales, and making the continent the world's largest light-duty plug-in regional market.

As of September 2016, sales in the European light-duty plug-in electric segment are led by Norway with over 121,300 units, followed by France with over 100,000 units registered by October 2016, and the Netherlands with almost 98,300 units registered at the end of September 2016.China is the world's leader in the plug-in heavy-duty segment, including electric, all-electric buses, and plug-in commercial and sanitation trucks. The stock of new energy vehicles sold in China totaled more than 733,000 units through September 2016. As of December 2015, China was the world's largest plug-in electric bus market with a stock of almost 173,000 vehicles.

Control system is constructed to maintain the output of plant or process suitably related to the input. Controller is a device introduced in the system to modify the error signal and to produce a control signal. It is also used to modify the transient response of the system. Controllers are used to improve Steady and Dynamic characteristics of the system. The controller may be located in forward path or it can be part of feedback control system. There are many controllers but most commonly used for industrial and various applications is PID Controller. Control of EV is not a simple task. Chan [1] Studied that last decade of 19th century, many companies produced EV in few countries. But it had limitations like storage capacity of battery. So the popularity of Internal Combustion Engine raised but in later stages due heavy emission CO_2 which led to environmental issues have triggered the use of eco-friendly vehicle also known as Electric Vehicle in massive level. The traction motor requires AC input. The DC output of battery is bucked or boosted using inverters (DC to AC).The frequency of output waveform depends on the switching rate it can be varied over wide range.

Mounir et.al [2] and Xue et.al [3] made a study on Electric Motor Drive selection issues for EV propulsion system. DC motor was considered initially for electric propulsion for EV. It is a conventional motor not used much now because of certain demerits such as Bulky construction, High maintenance cost and low efficiency. Due to above mentioned demerits DC motors are replaced by Induction motors. Even induction motor also has disadvantages such as high loss in rotor winding and low efficiency, low Power factor due *to* magnetizing component and poor starting torque and high in rush current.

Permanent Magnet Synchronous Motor is presently the most competent motor which overcomes the disadvantages occurring in DC motor by having compact structure, less maintenance cost and better efficiency due to absence of brushes and less rotor loss and high efficiency comparatively due to non-presence of rotor winding than induction motor. PMSM has higher power density because of the elimination of need for energy to produce magnetic poles. Considering the merits of this motor in EV has triggered this research towards using PMSM one of its type in electric vehicle due to its various advantages.

Qi Huang et.al [5] expressed that Control of Electric Vehicle is not a simple task especially in the operation of an EV which is essentially time variant (e.g. Operation parameters of EV and road conditions are always varying).

Karthik et.al [6] Apart from the growing popularity of Multi megawatt industrial drive applications, three phase voltage fed inverter are recently found to be an important component in developing the eco-friendly EV's.

Tomasz et al [10] discussed the remarkable merit of EV's i.e. the electric motors shows excellent performance in motion control which can be summarized as Torque generation is very quick and accurate, hence electric motor can be controlled much more quickly and precisely and Output torque is easily comprehensible of electric motor.

Currently the major limiting for wide-spread use of EV's is the short running distance per battery charge. Hence besides controlling the performance of vehicle, significant efforts have to be paid to the energy management of the batteries on the vehicle. The Constrained State Feedback Speed Control of Permanent Magnet Synchronous Motor (PMSM) is based on Model Predictive Approach. PMSM is used in motion control applications like industrial and robotics because of dynamic property and compact structure which makes it suitable for EV's. Controllers are used to improve Steady and Dynamic characteristics of the system. There are many controllers but most commonly used for industrial and various applications are PID controller.

The signal for the SFC controller is about two to three times smaller than the input of the system with PID controller. The controllers with similar poles had different zeros what influenced the shape of the response. Even though it is possible to tune PID controller in this case to have similar overshoot as SFC the example was chosen to show that even with the same poles the output may be different due to the differences between the controllers and different zeros.

II. DESIGN OF PMSM CONTROL

Electric Vehicle uses an Electric Motor for Traction, Chemical Batteries, and Super Capacitor's for the corresponding energy sources. In comparison with Internal Combustion Engine, Electric Vehicles have more advantages such as Absence of CO_2 emission, no usage of fossil fuel and Smooth Operations. Electric Vehicle consists of Battery, and two other major components such as Power Converter and Electric Motor. Power converter is an electronic device or circuitry that changes DC to AC. The output voltage and output current depends on the many switching methods of power converter. The source of Electric Vehicle is DC source which is obtained from the battery and most commonly used is Lithium-ion battery because it is environmental friendly, very rapid charges and very long lifespan. These batteries are also expected to find a prominent role as ideal electrochemical storage system in renewable energy plants as well as power system for sustainable vehicles such as EV and HEV. The battery of EV requires fuel delivered in the form of electricity to the vehicle through electric transmission system and Electric Motor supplies traction force to the wheels. Buck-Boost converter is used to step up or step down the output voltage according to the requirement. Voltage source inverter is used to change DC input voltage to AC output voltage which runs the PMSM motor and switching of VSI is sinusoidal pulse width modulation.

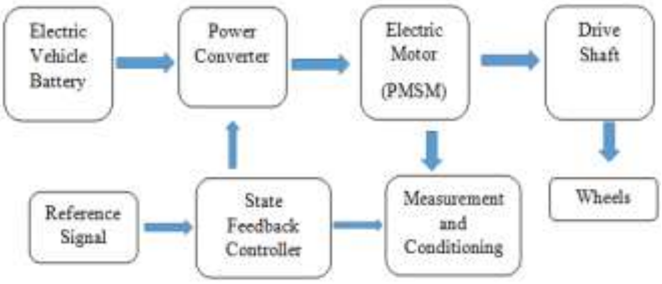

Figure 3 Functional Block Diagram

This Research is based on selection of effective Electric Vehicle motor and accurate controller to the motor for better performance of the EV. This project uses Permanent Magnet Synchronous Motor (PMSM) based Electric Vehicle with State Feedback Controller(SFC) which can be used in future because of its high efficiency to attain its objectives. To run this vehicle the Power Electronic plays a vital role for generating supply to motor which is AC supply. The Power electronic circuit uses is three phase Voltage Source Inverter which consist of 120 degree mode and 180 mode of switching. In this project 120 degree mode is used because it has advantages such as higher switching rate which is wide in range. The switching method used is VSI Sinusoidal Pulse Width Modulation because it enables to feed the motor with higher voltage with low harmonic distortions than conventional PWM inverter. While using battery as source of EV, the size of battery must be considered and with nominal voltage and current using Buck-Boost converter the voltage and current can be stepped up or stepped down according to the required output.

Using the above operations of the Power electronics circuits, EV source, motor and controller the speed control of PMSM is done by SFC controller. It is represented in following figure

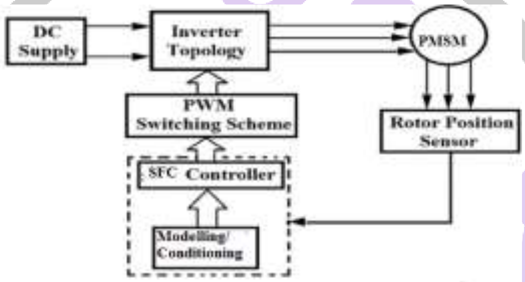

Figure 4 SFC Loop

A. Permanent Magnet Synchronous Motor

It consists of Multiphase stator and a rotor with Permanent Magnet. Machine can either be radially or axially oriented. Magnets can be stored in outer surface or buried inside rotor. Outer surface of rotor is comparatively better than buried inside because of control issues. Several different magnet materials are used and the most used ones are Ferrite because it is inexpensive but magnetically less powerful. So it is moved to rare-earth magnet Neodymium-Iron-Boron (NdFeB) or Samarium-Cobalt (SmCo) which is strongly magnetic and more resistant to temperature.

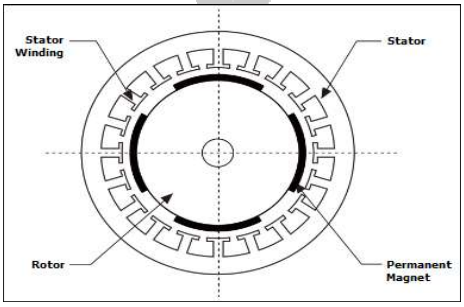

Figure 5 Structure of PMSM

Few applications of PMSM are Machine Tools, Robotics, Actuators and it's also used for higher power application like vehicle propulsion and industrial drives.

B. Control of PMSM Drive

A control system is constructed to maintain the output of plant or process suitably related to the input. Controller is a device introduced in the system to modify the error signal and to produce a control signal. Controllers are used to improve Steady and Dynamic characteristics of the system. The controller may be located in forward path or it can be part of feedback control system.

There are many controllers but most commonly used for industrial and various applications are PID controller .PID controller uses a 3 basic behaviour type or mode. They are Proportional (P), Integrator (I) and Derivative (D).

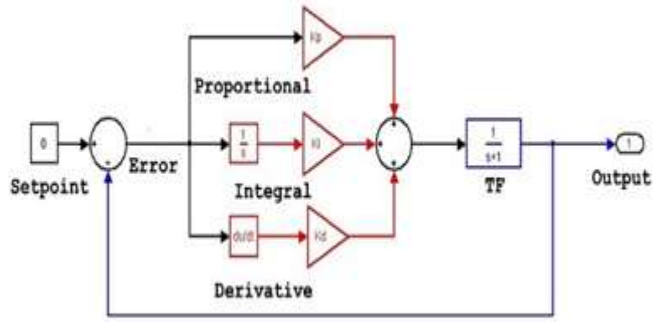

Figure 6 Schematic Representation of PID Controller

The PID controller is widely applied in feedback control of industrial processes. These controllers are described with their simple structure and principle. PID controllers also provide good performance for various systems. However, PID method in many cases such as parameter variations or disturbances is not appropriate. The parameters of PID controller (kp, ki, kd) are obtained by error and detection method. It is most commonly used and reliable method. It is necessary to tune the values in control loop to obtain the desired value and to acquire stability.

When PID controller is used for Electric Vehicle the results are not favorable.

- Slow starting performance of vehicle.
- While running vehicle small jerks occurs due to moisture in distributor gap. This leads to unbalance Power which damages the system.
- While applying brake, it does not stop smoothly. Efficiency of the vehicle is poor. These disadvantages may cause injury to the passenger.

In order to overcome some problem faced by PID controller, the other type of control methods can be developed such as state feedback controller (SFC). The control objectives of SFC are to Set-point tracking and Disturbance rejections.

State Feedback Controller is a method employed in feedback control system theory to place the closed loop poles of a plant in pre-determined locations in S-plane. The state space representation is

$$\dot{X} = AX + BU \quad \text{Input state equation} \qquad (1)$$

$$Y = CX + DU \quad \text{Output state equation} \qquad (2)$$

Where $\dot{X}$ = input state vector
A = state matrix of system
B = input matrix of system
C = output matrix of system
D = feed through matrix
Y = output vector
U = input or control vector

For the Design of State Feedback Controller there are 2 methods in which SFC is realized. They are Pole Placement Technique and Linear Quadratic Regulator Control (optimal control).

The method selected to design SFC is Pole Placement Technique.

Pole Placement Technique

It is similar to root locus method; poles of closed loop can be placed at desired locations. The difference between pole placement and root locus is that root locus places all dominant closed loop poles in desired location while pole placement places all closed loop poles at desired location. This is achieved by calculating the gain value from the state space matrix.

$$u = -Kx \qquad (3)$$

Where u = instantaneous state also known as feedback
K = state feedback gain matrix

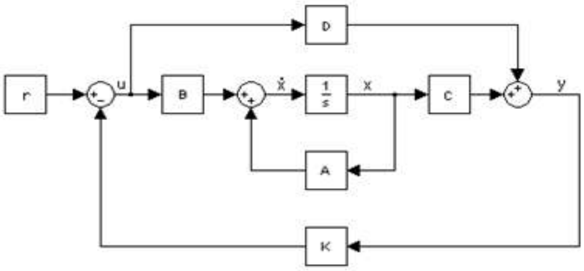

Figure 7 State Feedback Controller Structure

Advantages of State Feedback Controller is a solution applicable to wide range of practical control problems and currently is a powerful tool**.** Various Applications starting from aerospace, state space method has spread over the past 30 years into fields like Chemical, Bio-technological and other production process such as automation control, shipping and navigation and mechatronics.

III. MODELLING

The dq reference model has been developed on rotor reference frame

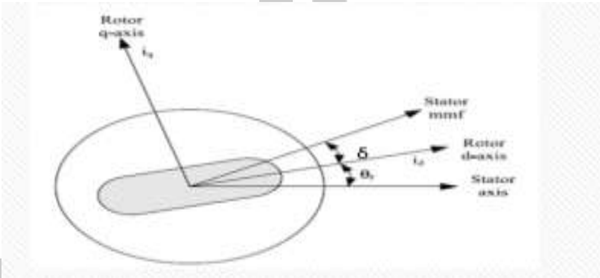

Figure 8 Rotor and Stator axis of PMSM

From the above diagram in an orthogonal d,q coordinate system that rotates at electrical speed of rotor the expression of voltage and flux equation of PMSM are given below

$$u_d = R_s i_d + \frac{d\varphi_d}{dt} - p\omega_m \varphi_q \quad (4)$$

$$u_q = R_s i_q + \frac{d\varphi_q}{dt} + p\omega_m \varphi_d \quad (5)$$

$$\varphi_d = L_d i_d + \varphi_f \quad (6)$$

$$\varphi_q = L_q i_q \quad (7)$$

Where u_d , u_q , φ_d, φ_q are voltages, currents and fluxes in d and q axis

L_d, L_q are inductances in d and q axis

R_s is resistance of stator

φ_f is permanent magnetic flus linkage

P is the number of pole pairs and

ω_m is rotor angular speed.

Substitute the flux equations;

$$\frac{d_{id}}{dt} = - \frac{R_s}{L_s} i_d + p\omega_m i_q + \frac{k_p}{L_s} u_{dc} \quad (8)$$

$$\frac{d_{id}}{dt} = - \frac{R_s}{L_s} i_d + p\omega_m i_q + \frac{k_p}{L_s} u_{dc} \quad (9)$$

The above equations are nonlinear, to make it linear new variables are define;

$$u_{md}(t) = \frac{p\ \omega_m\ (t)\quad L_s i_q\ (t)}{k_p} \quad (10)$$

$$u_{mq}(t) = \frac{p\ \omega_m(t)\ L_s\ i_d\ (t) + \varphi_f}{k_p} \qquad (11)$$

The Electromagnetic Torque described as follows

$$T_e = \frac{3}{2} p\ [\varphi_f i_q + (L_d - L_q)\ i_d i_q] \qquad (12)$$

$$L_{sd} = L_{sq} = L_s \quad \text{(due to symmetry)} \qquad (13)$$

$$T_e = \frac{3}{2}\ p\ [\varphi_f i_q] = k_t i_q \qquad (14)$$

Mechanical equation

$$\frac{d\omega_m}{dt} = \frac{1}{j_m}(T_e - T_l) \qquad (15)$$

$$\frac{d\theta_m}{dt} = \omega_m \qquad (16)$$

The mathematical model of a power electronic inverter has to be considered in order to design a PMSM speed controller. The inverter dynamics can be approximated by using the proportional element. As the dead time of transistors can be ignored the switching frequency is much higher than the electrical time constant of PMSM and inverter operated in a linear range.

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = kp \begin{bmatrix} u_{dc} \\ u_{qc} \end{bmatrix} \qquad (17)$$

Where, kp is an inverter gain

u_{dc} and u_{qc} are inverter control voltages for d and q

$$\frac{dx}{dt} = Ax + Bu + Ed \qquad (18)$$

A state space representation of non linear mathemcatical model in the rotating d-q reference frame.

$$\frac{dx(t)}{dt} = A(\omega_m)x\ (t) + Bu(t) + Ed\ (t) \qquad (19)$$

Where

$$A_{wm} = \begin{bmatrix} \frac{R_s}{L_s} & p\omega_m & 0 \\ -p\omega_m & \frac{-R_s}{L_s} & \frac{-p\varphi f}{L_s} \\ 0 & \frac{K_t}{J_m} & -\frac{B_m}{J_m} \end{bmatrix}$$

$$X(t) = \begin{bmatrix} i_d\ (t) \\ i_q\ (t) \\ \omega_m\ (t) \end{bmatrix} \qquad (20)$$

$$B = \begin{bmatrix} \frac{k_p}{L_s} & 0 \\ 0 & \frac{k_p}{L_s} \\ 0 & 0 \end{bmatrix} \qquad (21)$$

$$E = \begin{bmatrix} 0 \\ 0 \\ \frac{-1}{J_m} \end{bmatrix} \qquad (22)$$

$$u(t) = \begin{bmatrix} u_{sd}\ (t) \\ u_{sq}\ (t) \end{bmatrix} \qquad (23)$$

$$d(t) = T_l\,(t) \tag{24}$$

Where

i_d , i_q are current space vector components
R_s , L_s denote resistance and inductance of stator
φ_f is permanent magnet flux linkage
P is the number of pole pairs
ω_m is angular speed of PMSM shaft
J_m is moment of inertia
K_t is torque constant
B_m is viscous friction
T_l is unmeasured load

Where

$$A = \begin{bmatrix} \frac{-R_s}{L_s} & 0 & 0 \\ 0 & \frac{-R_s}{L_s} & 0 \\ 0 & \frac{K_t}{J_m} & \frac{-B_m}{J_m} \end{bmatrix}$$

$$X(t) = \begin{bmatrix} i_d\,(t) \\ i_q\,(t) \\ \omega_m\,(t) \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{K_p}{L_s} & 0 \\ 0 & \frac{K_p}{L_s} \\ 0 & 0 \end{bmatrix}$$

$$E = \begin{bmatrix} 0 \\ 0 \\ \frac{-1}{J_m} \end{bmatrix}$$

$$u(t) = \begin{bmatrix} u_{Ld}\,(t) \\ u_{Lq}\,(t) \end{bmatrix} = \begin{bmatrix} u_{sd}\,(t) + u_{md}\,(t) \\ u_{sq}\,(t) - u_{mq}\,(t) \end{bmatrix}$$

Thus the model of PMSM and SFC controller is presented to be the best speed control system of EV. In future, based on this review, motion control application can be made effective.

IV. DESIGN OF SFC

The flowchart for the SFC routine is shown in figure 9 and the following assumptions are made in pole placement technique
1. System is completely controllable.
2. State variables are measurable and available for feedback.
3. Control input is unconstrained.

A.Algortihm

There are 2 methods for designing SFC they are

- Bass-Gura approach
- Ackerman's Formula

In this paper Ackerman's Formula is used to design the controller **algorithm is given below**

Step 1: Start the SFC routine

Step 2: Obtain the State Space matrices A, B, C, D by modelling the motor speed, torque and inverter switching

Step 3: Check the step response and Pzmap for time behavior of output and location of poles

Step 4: The unstable pole or the pole near to origin is taken and it is replaced by new calculated pole value by using required time domain characteristics

Step 5: To place the poles at desired location the technique used is Pole Placement Technique also known as Ackermann's Formula

Step 6: Step 1: The gain value (k) formula can be calculated by using place command in MATLAB by using Ackermann's formula by K=place (A, B,p)

Step 7: After obtaining the k value matrix A is update and multiplying by gain value k i.e., (A-B*k)

Step 8: Replaced pole value makes the system stable and allows to achieve at desired locations

Flowchart of SFC routine :

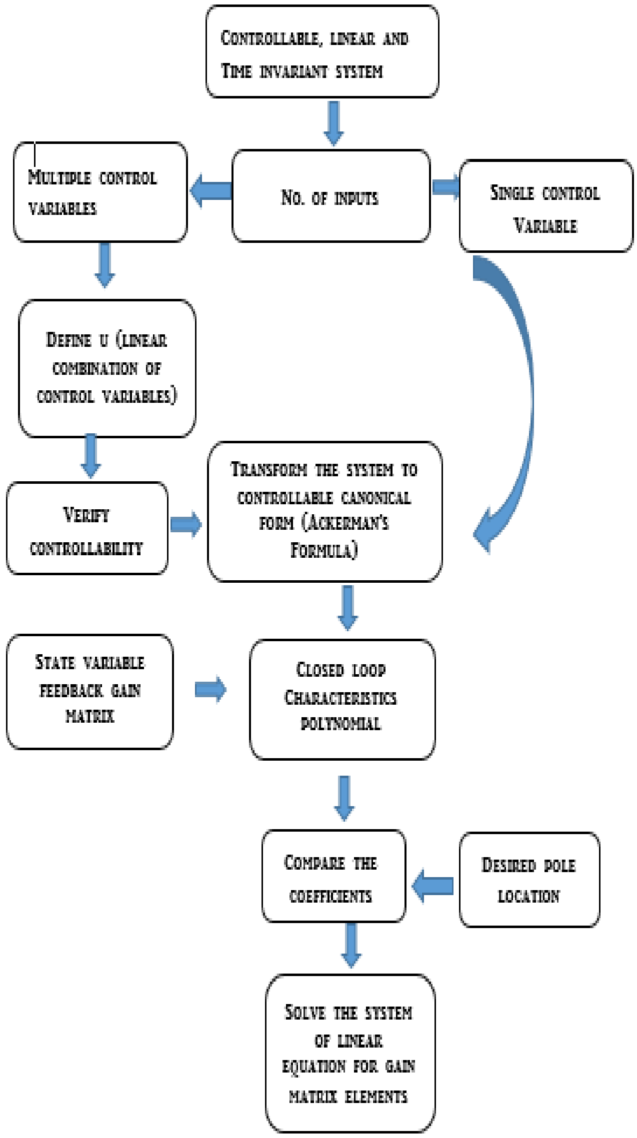

Figure 9 Flowchart of SFC Routine

B. Matlab coding

```
A=[-212.5 0 0; 0 -212.5 0; 0 3500 -11]
B=[23750 0 ;0 23750 ; 0 0]
C=[1 0 0]
D=[0 0]
p=eig (A)
p = [ -212.5000; -11.0000;  -212.5000]
p(2)=0.4721+186.76i
p(3)=0.4721-186.76i
p=1.0e+002*[-2.1250 -0.0047 + 1.8676i-0.0047-1.8676i]
 k= place (A,B,p)
 k = [ -0.0023    0.0019    0.0040;  -0.0004   -0.0071   0.0003]
```

V. SIMULATION

The performance of the Electric Vehicle modelled in section III, is analysed for the following 3 cases.

- Case 1 without controller
- Case 2 with PID controller
- Case 3 with SFC controller

The Operating voltage and current of the Battery, PMSM drive and Inverter Switches is shown in Table I. The design parameters of PMSM are presented in Table II.

Table 1 Ratings considered for Simulation

[Tomasz and Grzesiak (2016)]

Circuit components	Voltage(v)	Current(A)
Battery (Li-ion)	48v	6.5 Ah
PMSM	209v	3A
MOSFET	40v	14A

Table II Selected Parameters for drive

S.No	Parameters	Ratings
1.	Motor Power Rating	628W
2.	Motor Current Rating	3A
3.	Poles of motor	3
4.	Stator Resistance	0.85Ω
5.	Stator Inductance	4mH
6.	Moment of Inertia	1*10^-4 kg/m^2
7.	Voltage Terminal	209.3 V
8.	Rated Speed	1500 rpm
10.	Frequency	50kHz

A. Case 1 without controller

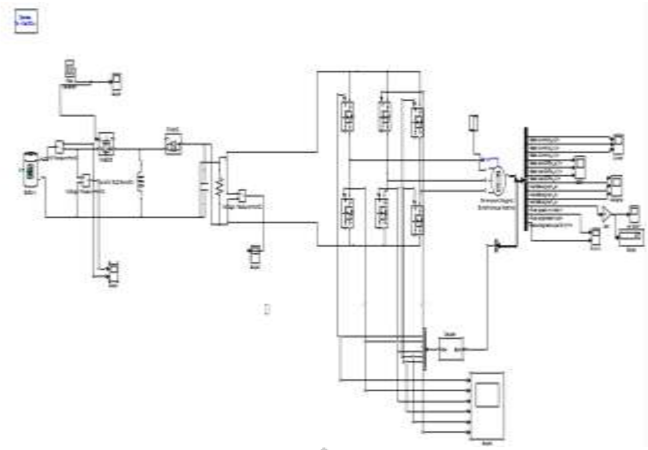

Figure 10 Simulation Diagram of PMSM without Controller

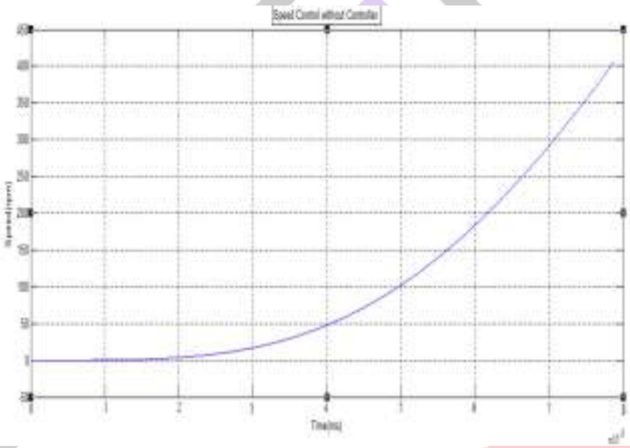

Figure 11 Starting Characteristics of PMSM without controller –Speed vs Time

Without Controller Speed Control in EV is very difficult as various disadvantages occur and the value of time domain parameters is also very high such as the rise time 6ms and settling time is 12ms.

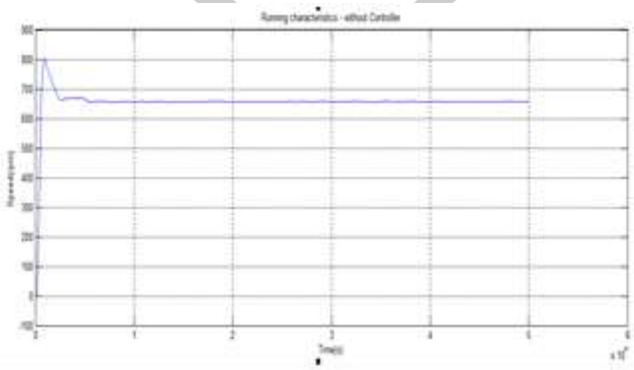

Figure 12 Running Characteristics of PMSM without controller-Speed vs Time

The running Characteristics shows that steady state error is 2.52% and time of settling is 9.33 ms. Thus running of EV is difficult without controller

B. Case 2 with PID controller

In this case PID controller is chosen as feedback because it's most commonly used for various applications. PID has many tuning methods to obtain the accurate output. The most common and reliable method is Error and Detection method. This is done by changing the derived values of kp, ki and kd from transfer function.

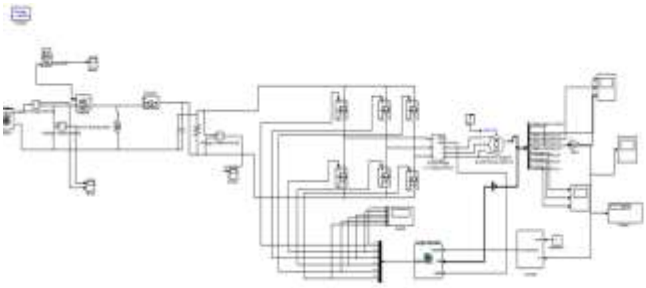

Figure 13 Simulation Diagram of PMSM with controller

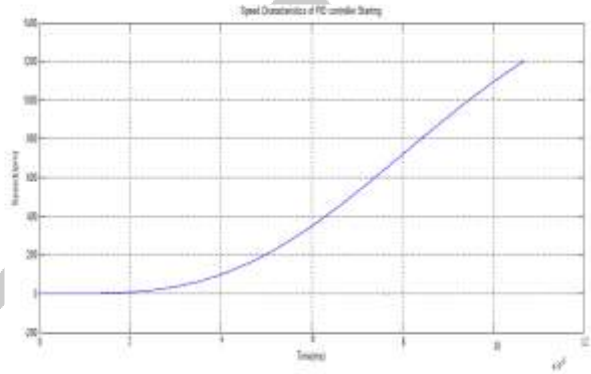

Figure 14 Starting Characteristics of PMSM with PID controller-Speed vs Time

From the above study of starting characteristics of Speed control of PMSM with PID controller for EV application it is found that rise time 5.6ms and settling time is 10ms of case 2 is better than case 1

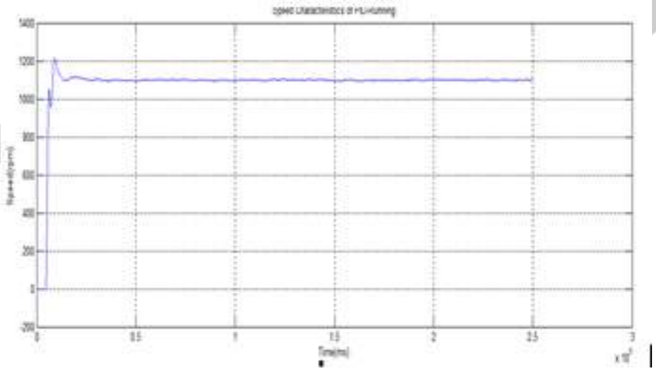

Figure 15 Running Characteristics of PMSM with PID controller Speed vs Time

From the above graph, controller action is observed and speed control of PMSM with PID running characterises of EV is found to be advantageous than without control as steady state error value and settling time is reduced by 1.68% and 0.8ms.

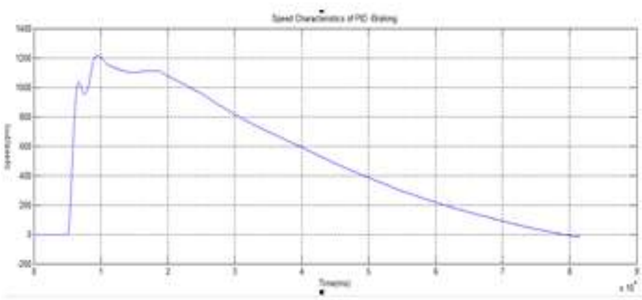

Figure 16 Braking Characteristics of PMSM with PID controller Speed vs Time

Braking Characteristics of PMSM with PID controller is obtained without controller action with the time domain parameters such as steady state error is 2.9% and fall time is 2ms unlike case 1

C. Case 3 with SFC controller

On finding few disadvantages using PID controller, SFC controller is used to overcome those faults. SFC is superior to PID in placing the closed loop poles in desired location by using Pole Placement Technique. Due to this advantage SFC is the best Controller for Speed control of PMSM for an EV.

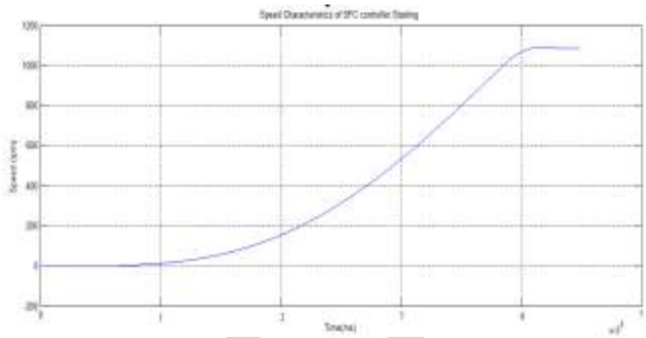

Figure 17 Starting Characteristics of PMSM with SFC controller-Speed vs Time

Comparing the above results it is seen and proved that Speed control of PMSM with SFC for EV is superior to PID controller and without controller. The time domain parameters like rise time is 5ms and settling time is 8ms

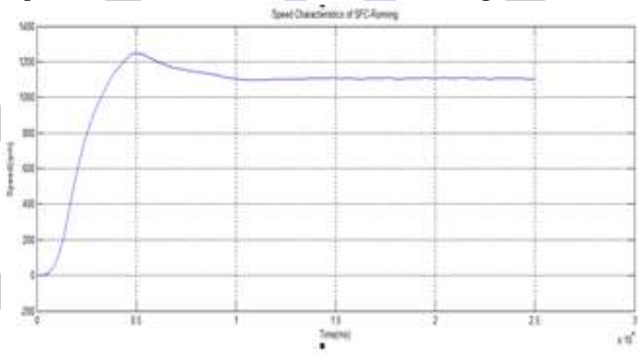

Figure 18 Running characteristics of PMSM with SFC controller Speed vs Time

Running Characteristic of PMSM with SFC is improved running of EV compare to PID controller and without controller with steady state error as 1.62% and settling time is 0.75ms

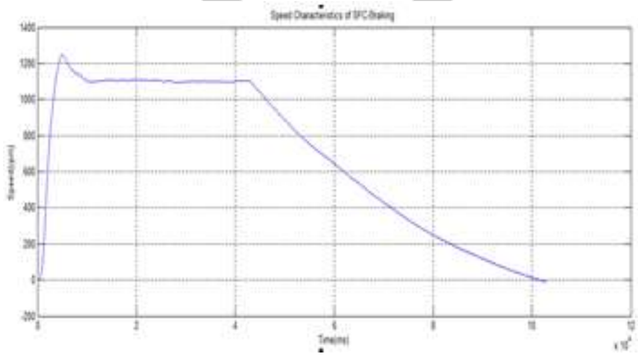

Figure 19 Braking Characteristics of PMSM with SFC controller

The characteristics obtained here with SFC controller is good compared to PID controller and without controller by reduced fall time and steady state error such as 1.5ms and 1.62%

VI. CONCLUSION

From the above discussion, the Speed control of PMSM without controller for EV has poor performance and Speed control of PMSM with PID controller is comparatively better yet expected objectives were not attained. So Speed control of PMSM with SFC controller is the best option.

From the above graphs in the pervious section, the Time-Domain characteritics of all the cases are compared in this section

Table III Starting Parameters

	Rise Time (Tr)	Peak Overshoot(Mp) %	Settling Time (Ts)	Steady State error %
without controller	6ms	16.7%	12ms	2.52%
PID controller	5.6ms	13.3%	10ms	1.68%
SFC controller	5ms	12.48%	8ms	1.63%

Table IV Running Parameters

	Settling Time (Ts)	Steady State error %
without controller	9.33ms	2.52%
PID controller	0.8ms	1.68%
SFC controller	0.75ms	1.62%

Table V Braking Parameters

	Fall Time (Tf)	Settling Time (Ts)	Steady State error %
PID controller	1.5ms	6.4ms	2.9%
SFC controller	2ms	5.5ms	1.62%

The above comparison of the Time-Domain Charactertitcs Speed control of PMSM with SFC is better in rise time, settling time, peak overshoot and steady state error .Thus Electric Vehicle system was simulated with three phase voltage source inverter and the system was implemented without controller(case 1), with PID controller (case 2) and SFC controller (case 3). The outcome of this project shows that SFC controller has better time domain characteristics than case 1 and 2 which gives effective results of operating conditions of EV.

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