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**[1] Ankit M Prajapati**
**[2] Ankit N Brahmbhatt**
**[3] Ashok D Pateliya**
**[4] Urvish A Shah**
**[5] Vilash N Chaudhari**

# Advanced Control Strategies of PMSM for Battery Electric Vehicle Application: A Review

***Abstract: -*** Due to the environmental concerns, limited availability of petroleum product and rapid rise in its cost leads the word’s in 21st century to accelerate the usage of Battery Electric Vehicle as a mean for transportation. This paper proposes a Permanent Magnet Synchronous Motor (PMSM) as a traction purpose in electric vehicle application. PMSM is a viable solution for BEV due to high efficiency, compact size, high power density, noise free operation and reliable. Acceleration, deceleration and braking is a major concern in BEV application demands a better dynamic performance over a wide range of PMSM. In this paper a review on the high-performance advanced control techniques like Field Oriented Control (FOC), Direct Torque Control (DTC) and Model Predictive Control (MPC) are included and compared.

***Keywords:*** Electric Vehicle, Permanent Magnet synchronous Motor (PMSM), Field Oriented Control (FOC), Direct Torque Control (DTC) and Model Predictive Control (MPC).

## I. Introduction

In recent years the energy and environment are the two major issues that attracted the attention of whole world for social development. This is due to the fact that the shortfall in petroleum resources, rising their cost and global warming impacted the human’s life. So, the world is moving towards the alternate sources of energy and specially for transportation the most environmental friendly solution is the use of Battery Electric Vehicle (BEV) over Internal Combustion Engine (ICE) vehicles. Due to the development of batteries, and the desire to reduce greenhouse gas emissions and improve urban air quality, the battery electric vehicle manufacturing industry has begun to receive attention from governments. Compared to internal combustion engine vehicles (ICEVs), the benefits of BEVs include zero exhaust emissions, higher efficiency, and the vast potential for reducing greenhouse gas emissions combined with the low-carbon power sector[1]. BEV can have an intelligent system for better performance, traffic safety, better driving range and better road utilisation.

In automotive application the vehicle has must operate for so many cycles of rapid acceleration, deceleration, braking, frequent start and stop in urban area and run on cruising speed on highways. That means the vehicle can undergo wide range of speed variation from zero to rated to cruising speed. So, the dynamic performance of a traction motor plays an important role for obtaining better performance.

This paper includes the various types of traction motors available for BEV. Different topologies of conventional, advanced and emerging electrical machines are presented. Why PMSM is a most widely adopted motor of BEV application is also mentioned here.

Next, modelling of PMSM and advanced control techniques are classified for Electric vehicle application for improving dynamic performance of PMSM. Advanced types consist of field-oriented control (FOC), direct-torque control (DTC), and model predictive control (MPC). For high impact automotive applications, vector control strategies, such as direct torque control (DTC) and field-oriented control (FOC), have frequently been applied[2].

## II. Traction Motors for BEV application

Traction motor in Electric vehicle application plays an important role. Selection of traction motors are more dependent on driving profile in cities and highways, where the vehicles must follow acceleration, deceleration, hill climbing, cruising and braking. So Fast and quick torque response is the most significant and main characteristic of high dynamic performance traction drive [3]. There are key requirements of traction motors are mentioned below [1].

1. High efficiency over wide speed - torque ranges, especially for regenerative braking.
2. High torque/power density and high starting torque for high acceleration and deceleration rates. High torque at low speeds (starting and hill climbing) and High power at high cruising speeds.

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[1] Assistant Professor, Electrical Engineering Department, Government Engineering College, Godhra.
[2] Assistant Professor, Electrical Engineering Department, Government Engineering College, Godhra.
[3] Assistant Professor, Electrical Engineering Department, Government Engineering College, Godhra.
[4] Assistant Professor, Electrical Engineering Department, Government Engineering College, Godhra.
[5] Assistant Professor, Electrical Engineering Department, Government Engineering College, Bhuj.
[2] *Corresponding author: Ankit N Brahmbhatt, Assistant Professor, Electrical Engineering Department, Government Engineering College, Godhra., anb.gec@gmail.com

3. Wide operating speed range including constant torque and power operations.
4. Easy-to-perform field-weakening at high speeds.
5. Small size and volume, lighter weight with high power and frequent starts/stops.
6. Good voltage regulation over a wide speed range and fast dynamic response.
7. High intermittent over load capability, typically twice the rated torque.
8. High reliability, robustness for harsh operating environments.
9. High fault tolerance operation and robust control.
10. Cost Economic and Rugged with simple maintenance
11. Low torque ripple, cogging torque and acoustic noise.
12. Low level of electromagnetic interference (EMI) noise, minimum total harmonic distortion factor.
13. Water proof, shock proof, and dust proof.
14. Motor drive needs high controllability, steady-state accuracy, and good transient performance.

A general classification of different types of electrical machines which includes conventional and advanced are presented [1], [4]–[6]. The classification in the below figure shows that in conventional self and Separately excited DC motor, AC induction and synchronous motor are included. But these motors have not been utilised for traction purpose due to advent of advanced machines which offer tremendous advantages over conventional machines.

Advanced Traction motor mainly includes Reluctance and Synchronous motor. Reluctance Motor classified into two: Switched Reluctance Motor (SRM) and Permanent Magnet aided SRM (PMaSRM). Synchronous Motors are further classified into three parts: Permanent magnet synchronous motor (PMSM), Synchronous Reluctance and Hybrid excitation. PMSM based on shape of the waveform of stator current further classified in two: Sinusoidal Excitation and Trapezoidal Excitation. In sinusoidal excitation according to the mounting of PM they are classified as Surface Mounted PMSM(SPMSM) and Interior PM motor (IPMSM). Permanent Magnet Brushless DC motor (PMBLDC), in which stator current shape is trapezoidal. PM assisted synchronous Reluctance Motor, By adding excitation windings to PMSM, the motor has both PMs and excitation windings and becomes a hybrid excited motor, which is PM Hybrid Excited Synchronous Motor (PM-HEM) [7]. PM assisted Synchronous Reluctance Motor (PMSyRM) combines the advantages of reluctance principle and Permanent Magnet.Fig.1 illustrate different kinds of traction motors for BEV application.

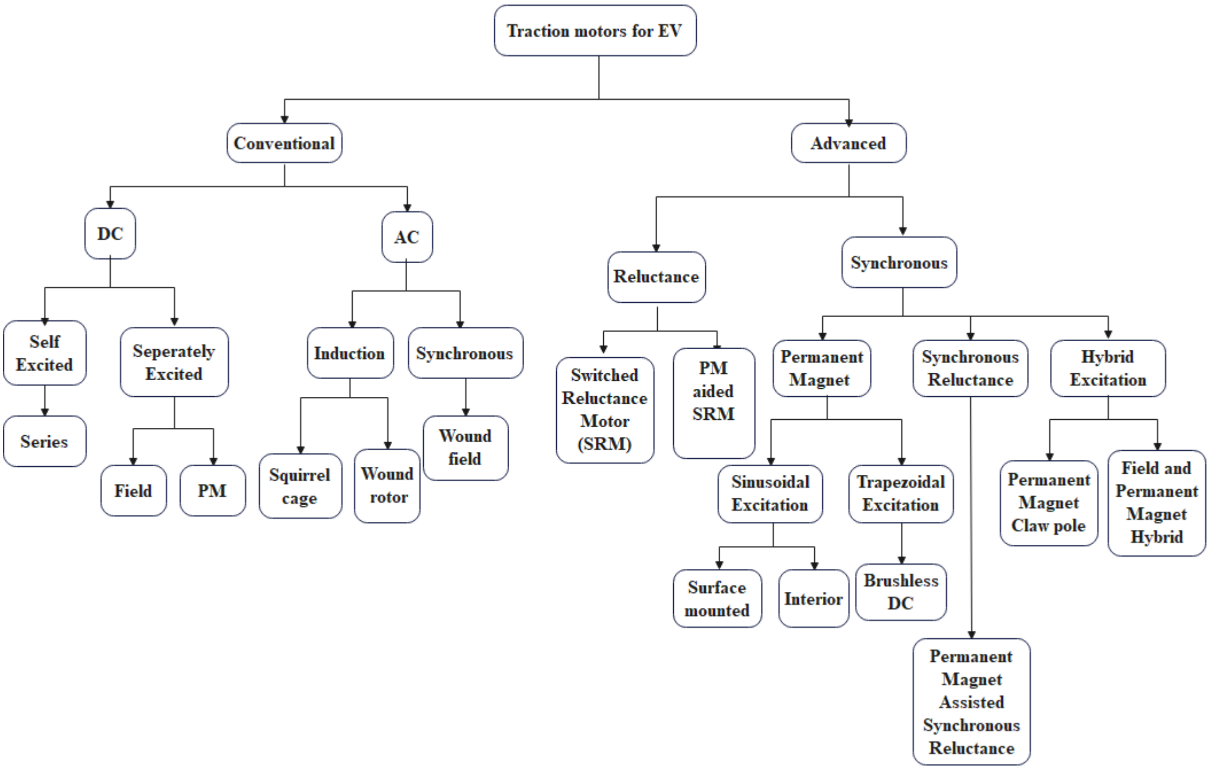


**Figure 1 Different kinds of traction motors for BEV application**

Electric motor technique has a set of their own benefits and drawbacks for driving a powertrain over a long period of development, much automotive industry started to change its motor structure and control techniques to improve BEVs performance[8]. After the investigation of BEV market from 2010-2020, we conclude that the motors that are currently installed in BEV propulsion systems mainly consists of the PMSM, IM, and SRM [9]. Out of all above traction motors authors concluded that PMSM is a most preferred choice over IM for BEV applications [3]. To improve its driving range, commercial passenger BEVs, such as Chevrolet Bolt, Ford Focus Electric, Hyundai Ioniq, and Jaguar I-Pace, Renault Kangoo ZE, Volkswagen E up, BYD E6, BMW i3, Tesla Model 3, NIO EC6, ES6, Renault Zoe, BJEV EC5, adopt PMSMs as the core propulsion component [5], [9]. Most of the PM motors use rare earth type magnet which are having high power density and high torque density [8]. PMSM has certain distinct feature which make it suitable for BEV applications are: presence of residual magnetism, high power density, high efficiency, smaller in size, light weight, low maintenance, low noise, reliable[4], [5], [8], [9].

There are also some drawbacks of PMSM mentioned by authors which leads to further research in this machine[5], [8], [9] like Permanent Magnet Demagnetization in field weakening during high speed, cost of rare earth PM, mechanical failure of PM, eddy current loss in PM, low fault tolerant capability. The comparison of various five most widely used traction motors are illustrated in table 1 given below[4].

| **Index** | **Brushless DC** | **Series** | **PMSM** | **SRM** | **IM** |
|---|---|---|---|---|---|
| **Cost** | High | Low | High | Medium | Medium |
| **Weight** | Low | Heavy | Medium | Medium | Medium |
| **Controller cost** | Very high | Low | High | High | High |
| **Maintenance requirement** | Negligible | Brushed wear | Negligible | Negligible | Negligible |
| **Efficiency** | High | Low | High | Less than PMDC | High |
| **Starting torque** | >175% of rated | >175% of rated | >200% of rated | Up to 200% of rated | High |
| **Speed range** | Excellent | Limited by brushes | Controllable | Controllable | Controllable |
| **Commutation** | Internal Electronic | Mechanical | External Electronic | External Electronic | External Electronic |
| **Pros** | Good torque and speed, fast response, tremendous power, long life | Inexpensive field weakening, maintains constant speed, higher starting torque | No torque ripple, higher torque, better performance, more reliable, less noisy | Low inertia, can be tailored for specific application, runs cool | High efficiency |
| **Cons** | Expensive | Bulky, limited speed, requires large field winding | Complex control, costly | Require position sensor, high acoustic noise, vibration, high torque ripple | Complex controller |

**Table 1. Comparison of various five most widely used traction motors**

## III Modelling of PMSM

Permanent Magnet Synchronous Motors are divided in to two parts: Surface Mounted Motors and Interior Permanent Magnet Motors. The stator of the permanent magnet synchronous motor has three-phase symmetrical windings of *A*, *B* and *C*, the rotor is equipped with permanent magnets, and the stator and rotor are coupled through air gap magnetic field [10]. To simplify the analysis following assumptions are made:

- Ignore winding leakage inductance
- Ignore the saturation of the core
- There is no damping winding on the rotor
- Magnetic circuit is assumed to be linear
- Emf induced in the stator winding is sinusoidal.

In PMSM the rotor windings are replaced by permanent magnets. Consequently the rotor flux is constant and the rotor current is zero [11]. Any modification in the air gap flux value is normally effected by the direct axis stator current [12]. The equation of the motor is a set of nonlinear time-varying equations related to the instantaneous position of the rotor, so the analysis of its dynamic characteristics is very difficult in the α-β system [13]. Therefore, mathematical model of PMSM in this coordinate system is not used in the analysis. The dynamic model of PMSM system is therefore presented in rotating d-q reference frame fixed in the rotor which is generally common for motor control.

$$y_{ds} = L_{ds}\, i_{ds} + Y_{m} \tag{1}$$

$$y_{qs} = L_{qs}\, i_{qs} \tag{2}$$

$$V_{ds} = R_s\, i_{ds} + L_{ds} \frac{di_{ds}}{dt} - \omega_r L_{qs}\, i_{qs} \tag{3}$$

$$V_{qs} = R_s\, i_{qs} + L_{qs} \frac{di_{qs}}{dt} + \omega_r\, (L_{ds}\, i_{ds} + \Psi_m) \tag{4}$$

$$T = \frac{3}{2}\, P\, (\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}) \tag{5}$$

Where $\Psi_{ds}$, $\Psi_{qs}$, $V_{ds}$, $V_{qs}$, $i_{ds}$ and $i_{qs}$ are respectively motor fluxes, voltages and currents in d-q reference frame. T is the electromagnetic torque, $\Psi_m$ is the Permanent Magnet flux, $\omega_r$ is the electrical angular velocity, $R_s$ is the stator resistance, $L_{ds}$ is the direct axis stator inductance and $L_{qs}$ is the quadrature axis stator inductance. In surface mounted PM motor $L_{ds} = L_{qs}$ [14] While in interior PM motor $L_{ds} < L_{qs}$ . Now the mechanical equations for the motor:

$$J \frac{d\omega_m}{dt} = T - T_l - B\omega_m \tag{6}$$

$$\omega_r = P\omega_m \tag{7}$$

Where J is the combined moment of inertia of motor and load, $T_l$ is the load torque and $\omega_m$ is the angular mechanical speed of the motor. Torque expression of motor (5) can be rewritten as

$$T = \frac{3}{2}\, P\, \frac{\Psi_s \Psi_m}{L_s} \sin\delta \tag{8}$$

From expression (8) we can say that the motor torque directly depends on stator flux, PM flux and sine of angle between the two.

## IV Advanced Control Strategies

### 4.1 Field oriented Control (Vector Control)

The most widely used linear strategy in medium and low power electrical drives is field oriented control (FOC), in which a decoupled torque and flux control is performed by considering an appropriate coordinate frame[15]. In this way motor torque and flux can be controlled independently. Thus the AC motors can be controlled like a DC motor greatly improves the control performance[10]. FOC imparts complete motor torque capability to the PMSM at speed ranges below rated speed and an efficient performance over a wider speed range[12]. A FOC to PMSM can achieve the advantages of high accuracy, high dynamic performance, wide speed range, low torque ripple, smooth starting in harsh working condition.

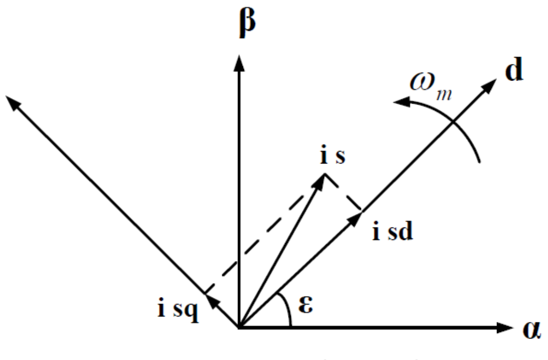


**Fig. 2 Vector diagram of FOC of PMSM**

The principle of vector control is the stator current vector can be decomposed in to direct axis component of current $i_{ds}$ and quadrature axis component of current $i_{qs}$, where $i_{ds}$ is the flux component of current and $i_{qs}$ is the torque component of current, shown in fig. 2. In PMSM due to the presence of Permanent magnet on rotor no need to generate flux by $i_{ds}$, so $i_{ds}$ is zero which establishes linear relationship between stator current and torque results in decreases the stator current and increases the efficiency. The stator flux can be expressed as stator current:

$$\Psi_s = \sqrt{\left((L_{ds} i_{ds} + \Psi_m)^2 + (L_{qs} i_{qs})^2\right)} \tag{9}$$

$$T = \frac{3}{2} P(\Psi_m i_{qs} + (L_{ds} - L_{qs}) i_{ds} i_{qs}) \qquad (10)$$

The block diagram shown below in Fig. 3 represents the FOC of PMSM with field weakening controller which can be operated over a wide speed range.

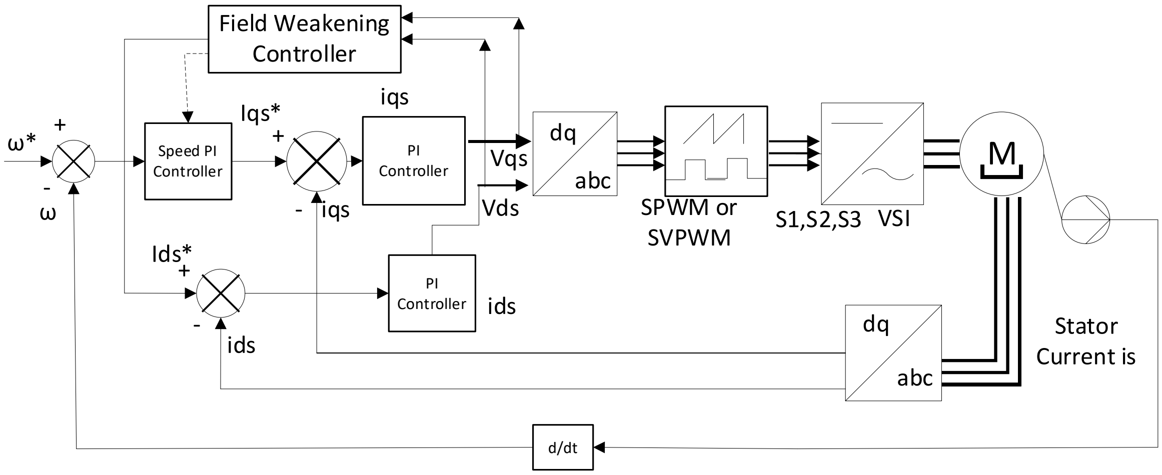


**Fig. 3 Block diagram of FOC for PMSM drive**

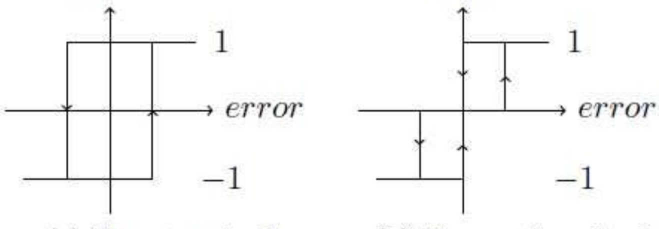
The complete FOC controller is a cascade closed control loop, composed of two internal PI-current controllers and an external speed PI controller. The internal PI controllers calculate the control voltage reference $V_{ds}$ and $V_{qs}$ based on the error between the current references $i_{ds}$ $*$and $i_{qs}$ $*$ and the measured currents, $i_{ds}$ and $i_{qs}$ , which are calculated by a stator current $i_s$ by transforming into synchronously rotating reference frame d-q. The external PI controller calculates the current reference based on the error between rotor speed reference ω∗ and real speed ω[5]. The instantaneous rotor position is sensed by a position sensor. In this cascaded type of closed loop control, the system time constants are so designed that the inner current loops respond faster than the outer speed loop. The output of PI controllers is saturated to limit the voltages and currents to rated values [12]. The voltage references generated $V_{ds}$ and $V_{qs}$ are again transformed into three phases which act as a control voltage for Sinusoidal Pulse Width Modulation (SPWM) or Space Vector Pulse Width Modulation (SVPWM). The gating signal thus obtained through SPWM or SVPWM is applied to the inverter which control the output voltage of the PMSM.

Similar to field weakening control which increases the speed range and maximum speed of vehicle, Maximum Torque per Ampere (MTPA) control can also be included in the controller to further increase the efficiency. FOC also having drawbacks of higher switching frequency, sluggish response and small bandwidth.

### 4.2 Direct Torque Control (DTC)

In BEV application fast torque response is a key factor for acceleration, deceleration and braking operation. Direct Torque Control provides smooth and faster torque response than FOC. In DTC the complex current control loop like FOC has been removed and no complex coordinate transformation required. Direct torque control of PMSM takes control of stator flux and electromagnetic torque directly and govern stator current and voltage indirectly by appropriate switching states of the inverter.

The main idea of DTC is to use two hysteresis controllers for electromagnetic torque and stator flux separately. The torque hysteresis controller is a three-level comparator with a bandwidth, whereas the flux hysteresis controller is a two-level comparator with another bandwidth as displayed in Fig. 4[16].



(a) Flux: two level (b) Torque: three level

**Fig. 4 Flux and Torque hysteresis comparator**

If φ =1, this means that real amount of stator flux linkage is lower than reference amount of flux. If φ =o, so real amount of stator flux linkage is higher than reference amount of flux. If T=1, real amount of electromagnetic torque is lower than command torque and so torque should have a raise, therefore by application of proper voltage vector and by raising angle θ , torque will increase. If T=-1, so real amount torque is higher than reference torque amount[16]. The switching table shown below shows which voltage vector needs to be selected at particular instant in any sector from $\Theta_1$ to $\Theta_6$.

| Flux (φ) | Torque (T) | Position of Stator flux vector ($\Psi_s$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | $\Theta_1$ | $\Theta_2$ | $\Theta_3$ | $\Theta_4$ | $\Theta_5$ | $\Theta_6$ |
| Φ=1 | T=1 | $V_2$ (110) | $V_3$ (010) | $V_4$ (011) | $V_5$ (001) | $V_6$ (101) | $V_1$ (100) |
| | T=0 | $V_7$ (111) | $V_0$ (000) | $V_7$ (111) | $V_0$ (000) | $V_7$ (111) | $V_0$ (000) |
| | T=-1 | $V_6$ (101) | $V_1$ (100) | $V_2$ (110) | $V_3$ (010) | $V_4$ (011) | $V_5$ (001) |
| Φ=0 | T=1 | $V_3$ (010) | $V_4$ (011) | $V_5$ (001) | $V_6$ (101) | $V_1$ (100) | $V_2$ (110) |
| | T=0 | $V_0$ (000) | $V_7$ (111) | $V_0$ (000) | $V_7$ (111) | $V_0$ (000) | $V_7$ (111) |
| | T=-1 | $V_5$ (001) | $V_6$ (101) | $V_1$ (100) | $V_2$ (110) | $V_3$ (010) | $V_4$ (011) |

**Table 2. Switching table for DTC**

Stator voltage equation in fixed reference frame is:

$$V_s = R_s i_s + \frac{d\Psi_s}{dt} \tag{11}$$

If stator voltage drop neglected then the change in stator flux is directly proportional to applied stator voltage.

$$\Delta\Psi_s = V_s \Delta t \tag{12}$$

The decoupled control of torque and flux can be obtained by acting on the radial and tangential components of stator flux vector. According to equation (12) this control can be achieved by applying stator voltage vector in the same direction. The tangential component of stator voltage control the angle between the stator flux $\Psi_s$ vector and permanent magnet flux $\Psi_m$ vector. Thus torque can be controlled by tangential components of stator voltage. The radial component control the amplitude of stator flux vector. Fig 5. Shown below how stator voltage vector control the torque and flux for two level VSI, In which α-β frame is divided into six sectors S=1,….,6. From diagram it can be seen that for sector 1 voltage vector $V_2$ increases flux and torque, voltage vector $V_3$ decreases flux and increases torque, voltage vector $V_5$ decreases flux and torque and voltage vector $V_6$ increases flux and decreases torque.

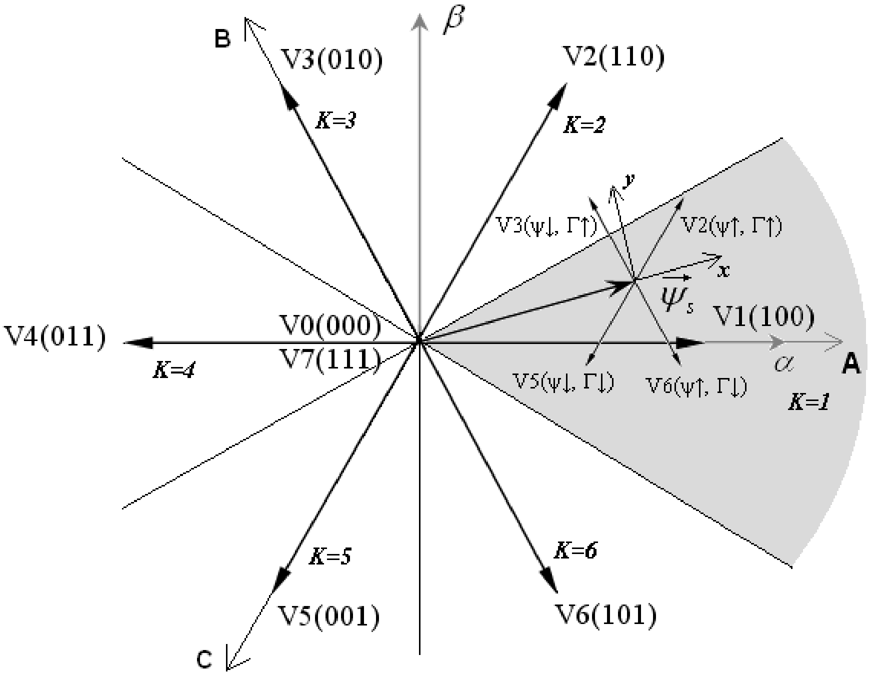


**Fig. 5 Control of stator flux and torque by stator voltage vector**

Fig. 6 shows the block diagram of Direct Torque Control of PMSM. In which rotor position and stator phase currents are fed into the estimator where stator flux, torque and speed are estimated. Here first three phase stator current is transformed into the two phase and once stator flux is calculated it can be then transformed from d-q to the stationery frame α-β.

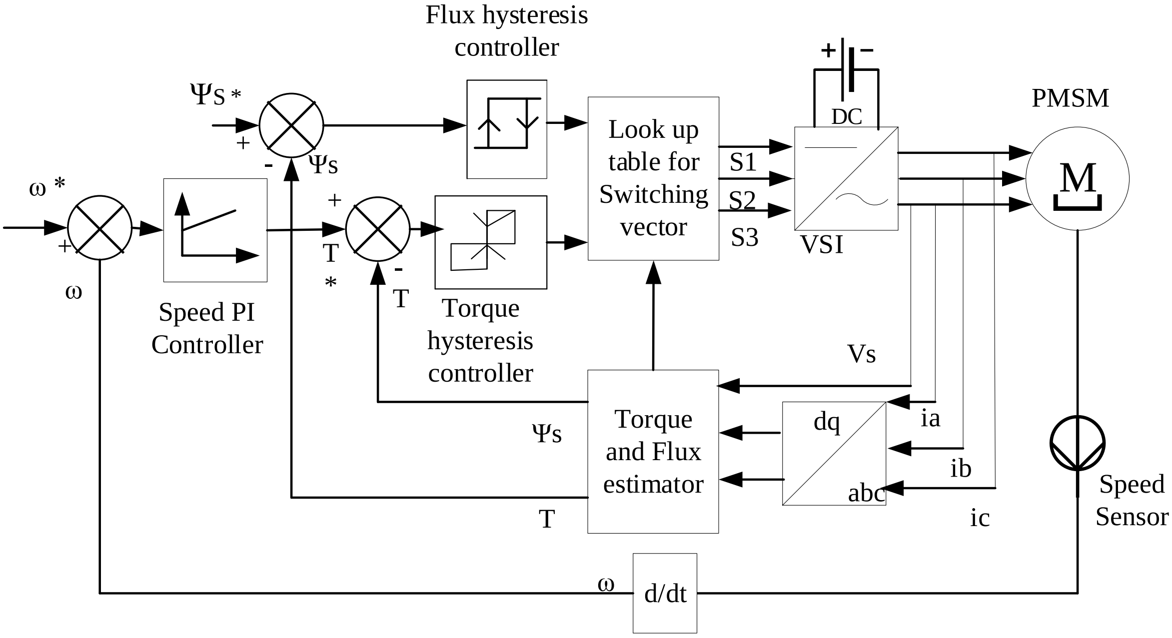


**Fig. 6 block diagram of Direct Torque Control of PMSM**

After that reference value of stator flux and torques are compared with the estimated values where stator flux and torque error is generated and which is fed to two level flux hysteresis controller and three level torque hysteresis controller respectively. The output of the hysteresis comparator is fed to the look up table (table no. 2), which decides which voltage vector need to be applied to the inverter. Look up table also requires input of stator voltage vector position which can be obtained from estimator block. The flux hysteresis bandwidth mainly affects the motor current distortion in terms of low-order harmonics. Switching frequency and switching losses are mainly affected by the torque hysteresis bandwidth[5]. Variable switching frequency in DTC leads to high current and torque ripple which requires further study. Some authors proposed methods to reduce current and torque ripple but still issues could not be solved completely.

### 4.3 Model Predictive Control

The field oriented control (FOC) and direct torque control (DTC) are the two most popular control approaches for the control of permanent magnet synchronous machines (PMSMs)[17]. In FOC inner current control bandwidth and coordinate transformation limits the dynamic response of PMSM, the tuning of PI controller gain is very complex, PWM creates delay in the controller design. While DTC requires neither a modulator nor PI controller, achieves fast dynamic response, easier implementation, absence of modulator avoids delay and all the calculations are implemented in stationery coordinate it is simple[18],[19]. Despite above merits conventional DTC suffers from high torque ripple, flux ripple, high THD, variable switching frequency and excessive acoustic noise. To mitigate above issues DTC is combined with other methods like MP-DTC, DTC with sliding mode, optimization of switching voltage vector [2], [19], [20].

In recent years, Model Predictive Control (MPC) has acquired popularity as a reliable control strategy. By properly using the system model to predict the output response, MPC techniques allow to choose the optimal control action that minimizes a desired cost function. Within the power electronic field[18], Many efforts to utilize MPC in electrical drives have been made in last decade. Electrical drive systems are essentially an application sub area of power electronics because the drives for electric machines, i.e. power convertors, are a class of power electronics' applications. When controlling electrical drives, MPC contains merits such as faster dynamics, easier concept of design, simpler structure and realization, etc [19]. MPC was extensively employed to further application regions, such as power quality, machine drive, grid-connected converters, and controllable power supplies. MPC has been widely investigated for AC drives. It can be extensively applied for IM, PMSM, BLDC, Multiphase machines.

For Electric vehicle application MPC is more viable solution as it is flexible so torque ripples, efficiency and switching frequency can be designed as per BEV requirements, fast torque response makes braking faster which add safety feature, insensitive to parameter variation, can be combined with existing controller to improve steady state and dynamic response.

Model Predictive control is broadly classified into two main categories: Continuous Control Set MPC (CCS-MPC) and Finite Control Set MPC (FCS-MPC). In CCS MPC modulator is required to generate switching state of the inverter, on the other hand FCS MPC requires no modulator as finite number of switching states are applied to the inverter to solve optimization problem. Though more computational efforts are needed, it can be applied to situations that requires continuous reference voltage vectors, which is a limitation for the application of conventional FCS-MPC generating only discrete switching states. In light of the easiness for nonlinearities and constraints control, compared to CCS-MPC, FCS-MPC has more overall advantages [19].

The process of MPC basically divided into three parts:

- First, the present system states are predicted with measured current and voltage, which is called the delay compensation.
- Then, the possible system states at the next moment under different voltage vectors are predicted through the predictive model.
- Finally, the optimal voltage vector is selected through the cost function.

The process of basic MPC is shown in the fig. 7.

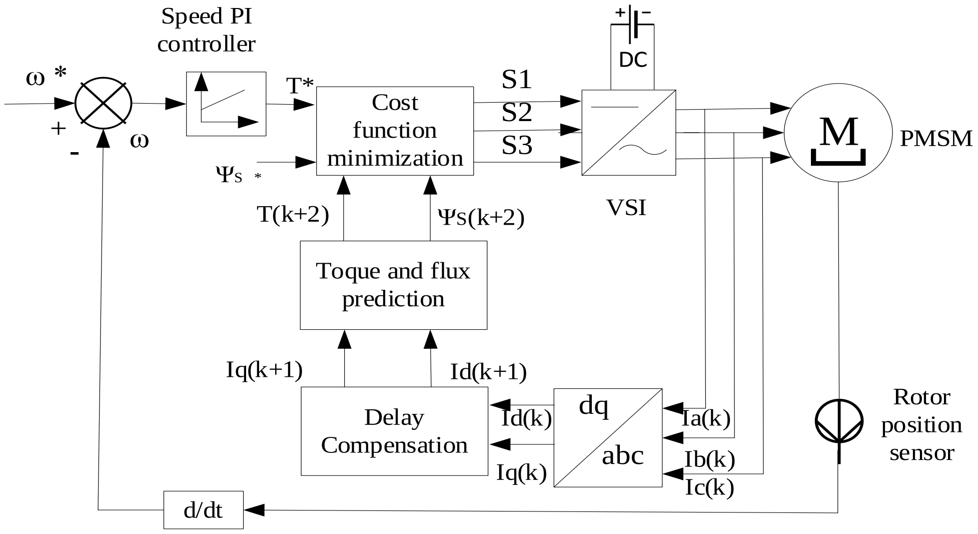


**Fig. 7 Model Predictive Control scheme**

Here discrete time machine model is used for predicting the future behaviour of stator current. Using Euler's approximation predicted stator current in dq reference frame can be obtained by equation[21]

$$\frac{di}{dt} = \frac{i(k+2)-i(k+1)}{T_s} \tag{13}$$

Using measured current $i_a(k)$, $i_b(k)$ and $i_c(k)$ d axis and q axis current $i_q(k)$ and $i_d(k)$ are obtained. All the calculations and decisions are not implemented at kth instant and cannot be applied immediately, but applied actually in (k+1)th instant. So to eliminate this one step delay the variables of $\Psi_s(k+2) and\ T(k+2)$ should be used rather than $\Psi_s(k+1)\ and\ T(k+1)$ for evaluation of cost function. Using measured current and all the switching voltage vector V(k) future current $i_q(k+2)$ and $i_d(k+2)$ are estimated[21],

$$i_{qs}(k+2) = (1-\frac{R_s T_s}{L_s})i_{qs}(k)-T_s\omega_r i_{ds}(k)-\Psi_m\omega_r T_s+\frac{T_s}{L_s}V_{qs} \tag{14}$$

$$i_{ds}(k+2) = (1-\frac{R_s T_s}{L_s})i_{ds}(k)+T_s\omega_r i_{qs}(k) +\frac{T_s}{L_s}V_{ds} \tag{15}$$

Using these equations of predictions of stator current the future value of $i_d$ and $i_q$ are calculated for each of seven voltage vectors generated by inverter. Using these predicted values the optimized switching voltage vector which minimizes the cost function is selected and applied to the inverter switches. The equation of cost function

$$g = |i_d^*- i_d|+| i_q^*- i_q| + \lambda\| V(k+2)-V(k+1)\| \tag{16}$$

Here equation $|i_d^* - i_d| + |i_q^* - i_q|$ are the reference following term, $\lambda$ is the weighting factor and $\|V(k+2)-V(k+1)\|$ is the control effort. Control effort can be reduced by increasing the weighting factor.

The step by step implementation flow chart of MPC is shown in the fig. 8 below where N= total number of switching voltage vectors[22].

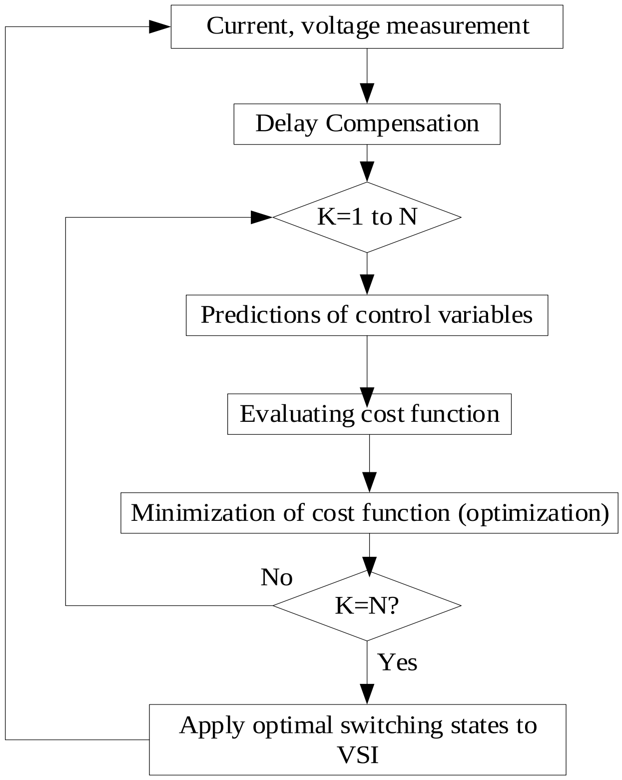


**Fig. 8 Step by step flow chart of MPC**

## V. Comparison between Advanced Control Strategies

The table no. 3 shown below presents a comparison between these three methods[4], [5], [11], [23]–[25].

| Aspects | FOC | DTC | MPC |
|---|---|---|---|
| Structure | • One speed PI and two current controller<br>• SPWM or SVPWM required | • One speed PI and two hysteresis controller<br>• Switching table required | • One speed PI and one hysteresis controller<br>• Cost function required |
| Advantages | • Fixed switching frequency<br>• Low computation burden<br>• Low THD<br>• Low torque ripple<br>• Low noise | • Low computation burden<br>• Low switching frequency<br>• Fast transient response<br>• Ease of tuning<br>• Low complexity<br>• Easy implementation | • Low switching frequency<br>• Ease of tuning<br>• Fastest transient response<br>• Large control bandwidth<br>• Constraints can be included<br>• Less torque ripple |
| Issues | • High switching frequency<br>• All parameters required except resistance<br>• Slow response<br>• Modulator required<br>• Difficult to tune<br>• Small current control bandwidth | • High THD<br>• Small current control bandwith<br>• High ripple and distortion<br>• Sensitive to stator resistance | • High computation burden<br>• Variable switching frequency<br>• Parameter uncertainty<br>• Poor stability |

**Table 3 Comparison between FOC, DTC and MPC for BEV application**

## VI. Conclusion

In this paper comparison between various traction motors used for BEV applications and brief introduction of three main advanced control strategies FOC, DTC and MPC are discussed. The comparison between various traction motors and control strategies are presented in this paper. Each motor has several advantages and limitation, but PMSM is the most viable solution for BEV application due to high power density, high efficiency, low noise, fast dynamic response, high power to weight ratio, low cost and low maintenance. MPC is an advanced and preferred control strategy for electric vehicle as it has faster dynamic response, constraints inclusion, less torque ripple. MPC can be combined with other control strategies to improve the dynamic performance of the PMSM. But still some future work required for better performance, include reduced computational burden, reduced THD, improve stability, fast dynamic response. MPC is a future control strategy of PMSM for BEV application.

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