



# Field Oriented Control of Permanent Magnet Synchronous Motor

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*Abstract-Today, “electric platform” based commercial and military aerospace, land vehicles and weapon systems are using adjustable speed PM motor systems to replace older fixed speed motors that have mechanical gearboxes. PMSM (Permanent Magnetic Synchronous Motor) has been increasingly used in many high performance application due to its advantages of high power density, high power factor and efficiency. Firstly, a SVPWM scheme, vector control method and fuzzy controller are derived and applied in the speed control IC of PMSM drive. Secondly, the Very-High-Speed IC Hardware Description Language (VHDL) is adopted to describe the behavior of the fore mentioned control algorithms. 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).*

**Keywords:** FOC; PMSM; SVPWM; VHDL; vector control

## I. Introduction

The Adjustable Speed Drives (ADS) are generally used in industry. In most drives AC motors are applied. The standard in those drives are Induction Motors (IM) and recently also Permanent Magnet Synchronous Motors (PMSM) are offered. Variable speed drives are widely used in application such as pumps, fans, elevators, electrical vehicles, heating, ventilation and air-conditioning (HVAC), robotics, wind generation systems, ship propulsion, etc. Previously, DC machines were preferred for variable speed drives. However, DC motors have disadvantages of higher cost, higher rotor inertia and maintenance problem with commutators and brushes. In addition they cannot operate in dirty and explosive environments. The AC motors do not have the disadvantages of DC machines. Therefore, in last three decades the DC motors are progressively replaced by AC drives. The responsible for those result are development of modern semiconductor devices, especially power Insulated Gate Bipolar Transistor (IGBT) and Digital Signal Processor (DSP) technologies. The most economical IM speed control methods are realized by using frequency converters. Many different topologies of frequency converters are proposed and investigated in a literature. However, a converter consisting of a diode rectifier, a dc link and a Pulse Width Modulated (PWM) voltage inverter is the most applied used in industry.

### A. Permanent Magnet Synchronous Motors

PMSM has been used in many automation fields such as robot, metal cutting machines, precision machining, etc., because its advantages of superior power density, high performance motion control with fast speed and better accuracy. Up to

now, there are many control methods have been studied to control the speed of PMSM such as adaptive control, PID control, intelligent control etc. Many conventional controls use Digital Signal Processor (DSP) in most studies. Unfortunately, DSP suffers from long time of development and exhaust resources of CPU. The novel technology of FPGA with great advantages of programmable hard-wired feature, fast computation ability, shorter design cycle, embedded processor and low power consumption and higher density on the other hand can provide an alternative solution for these issues and is more suitable for the implementation of Digital System than conventional DSPs. Vector control techniques have made possible the application of PMSM motors for high performance applications where traditionally only dc drives were applied. The vector control scheme enables the control of the PMSM in the same way as a separately excited DC motor operated with a current-regulated armature supply where then the torque is proportional to the product of armature current and the excitation flux. Similarly, torque control of the PMSM is achieved by controlling the torque current component and flux current component independently.

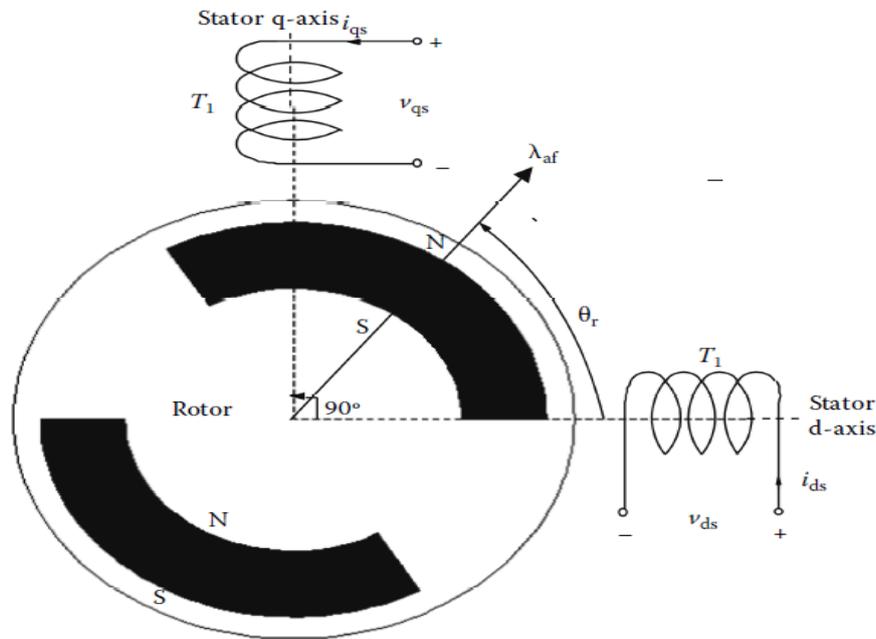


Fig. 1 PMSM Motor

### B. Synchronous Motor Operation

Synchronous motors are generally preferred whereas constant speed is desired under varying loads. Their speed can be adjusted by using inverters or adjustable voltage or frequency source. Their size and inertia moment values are smaller compared to the DC motors. Their efficiency and power factors are larger compared to asynchronous motors. As known an electrical motor needs two fluxes in order to constitute working induction in the air gap. This principle is the base rule for any motor design. Moreover PMSM can be constructed by replacing the DC induction coils of the rotor by permanent magnets, thus the magnetic flux on the rotor is supplied by the magnets

- Synchronous motor construction: Permanent magnets are rigidly fixed to the rotating axis to create a constant rotor flux. This rotor flux usually has a constant magnitude. When energized, the stator windings create a rotating electromagnetic field. To control the rotating magnetic field, it is necessary to control the stator currents.
- The actual structure of the rotor varies depending on the power range and rated speed of the machine. Permanent magnets are suitable for synchronous machines ranging up-to a few Kilowatts. For higher power ratings, the rotor usually consists of windings in which a dc current circulates. The mechanical structure of the rotor is designed for the number of desired poles, and the desired flux gradients.
- The interaction between the stator and rotor fluxes produces a torque. Since the stator is firmly mounted to the frame, and the rotor is free to rotate, the rotor will rotate, producing a useful mechanical output.
- The angle between the rotor magnetic field and the stator field must be carefully controlled to produce maximum torque and achieve high electro-mechanical conversion efficiency. For this purpose a fine tuning is needed after closing the speed loop using the sensor less algorithm in order to draw the minimum amount of current under the same speed and torque conditions.

## II. Existing Method

One way of controlling AC motors for variable speed applications is through the open loop scalar control, which represents the most popular control strategy of squirrel cage AC motors. Nowadays it is used in applications, where information about the angular speed need not be known. It is suitable for a wide range of drives as it ensures robustness at the cost of reduced dynamic performance. Typical applications are pump and fan drives and low-cost drives. The main idea of this method is variation of the supply voltage frequency abstractedly from the shaft response (position, angular speed). The magnitude of the supply voltage is changed according to the frequency in a constant ratio. Then the motor is in the condition, where the magnetic flux represents the nominal value and the motor is neither overexcited nor under excited. The most advantage of this simple method is running in a sensor less mode because the control algorithm does not need information about the angular speed or actual rotor position. On the contrary, the big disadvantages are the speed dependence on the external load torque, mainly for IM, and reduced dynamic performances.

### A. Scalar Control V/F Of PMSM

Constant volt per hertz control in an open loop is used more often in the squirrel cage IM applications. Using this technique for synchronous motors with permanent magnets offers a big advantage of sensor less control. Information about the angular speed can be estimated indirectly from the frequency of the supply voltage. The angular speed calculated from the supply voltage frequency according to can be considered as the value of the rotor angular speed if the external load torque is not higher than the breakdown torque. The mechanical synchronous angular speed  $\omega_s$  is proportional to the frequency  $f_s$  of the supply voltage

$$\omega_s = \frac{2\pi f_s}{p} \quad \dots(1)$$

where  $p$  is the number of pole pairs. The RMS value of the induced voltage of AC motors is given as

$$E_f = \sqrt{2\pi f_s N s k w \phi} \quad \dots(2)$$

. The electromagnetic torque of the synchronous motor, when the stator resistance  $R_s$  is not negligible, is given as

$$T_e = -\frac{m}{\omega_s} \left[ \frac{V_{sph} E_f}{Z_d} \sin(V_L - \alpha) - \frac{E_f^2 R_s}{Z_d} \right] \quad \dots(3)$$

where  $V_{sph}$  is the stator terminal phase voltage,  $E_f$  is the induced voltage generated by the field current excitation,  $R_s$  is the stator resistance

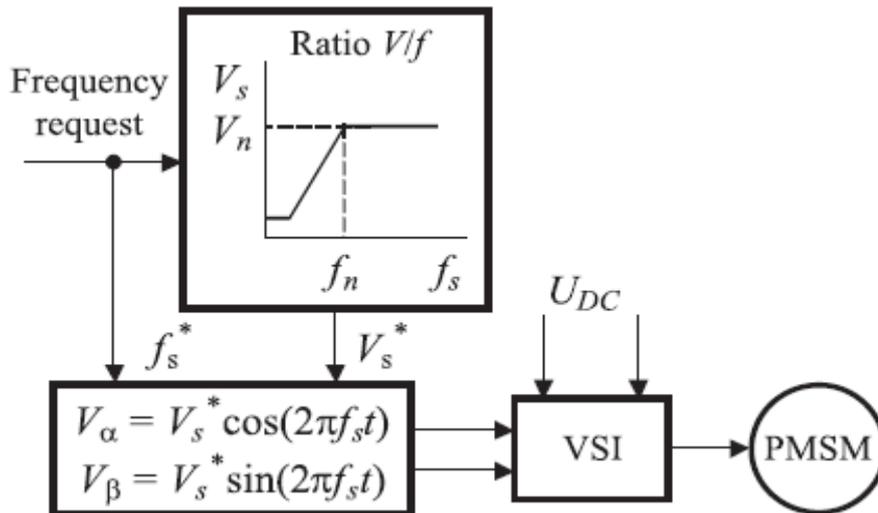


Fig. 2 Stator voltage  $V_{sph}$  versus stator frequency  $f_s$

### III. Proposed System

#### A. Field Oriented Control

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, advanced control strategies can be implemented, which uses mathematical transformations in order to decouple the torque generation and the magnetization functions in the PM motors. Such decoupled torque and magnetization control is commonly called rotor flux oriented control, or simply FOC. Independent Control of Torque and Speed can be achieved by using the Field Oriented Control where two currents responsible for Torque and Field are separately resolved and Controlled (q axis current and d axis current). The Project work will be implementing the FOC Algorithm in VHDL Vector control techniques have made possible the application of PMSM motors for high performance applications where traditionally only dc drives were applied. The vector control scheme enables the control of the PMSM in the same way as a separately excited DC motor operated with a current regulated armature supply where then the torque is proportional to the product of armature current and the excitation flux. Similarly, torque control of the PMSM is achieved by controlling the torque current component and flux current component independently.

The outputs are designated  $i_{s\alpha}$  and  $i_{s\beta}$ . These two components of the current are the inputs of the Park transformation that provide the current in the d, q rotating reference frame. The  $i_{sd}$  and  $i_{sq}$  components are compared to the references  $i_{sdref}$  (the flux reference) and  $i_{sqref}$  (the torque reference).

At this point, this control structure shows an interesting advantage: it can be used to control either synchronous or HVPM machines by simply changing the flux reference and obtaining rotor flux position. As in synchronous permanent magnet a motor, the rotor flux is fixed determined by the magnets; there is no need to create one. Hence, when controlling a PMSM,  $i_{sdref}$  should be set to zero. As HVPM motors need a rotor flux creation in order to operate, the flux reference must not be zero. This conveniently solves one of the major drawbacks of the “classic” control structures: the portability from asynchronous to synchronous drives. The torque command  $i_{sqref}$  could be the output of the speed regulator when you use a speed FOC. The outputs of the current regulators are  $V_{sdref}$  and  $V_{sqref}$ ; they are applied to the inverse Park transformation. The outputs of this projection are  $V_{s\alpha ref}$  and  $V_{s\beta ref}$ , which are the components of the stator vector voltage in the  $(\alpha, \beta)$  stationary orthogonal reference frame. These are the inputs of the space vector PWM. The outputs of this block are the signals that drive the inverter. Note that both Park and inverse Park transformations need the rotor flux position. Obtaining this rotor flux position depends on the AC machine type (synchronous or asynchronous machine).

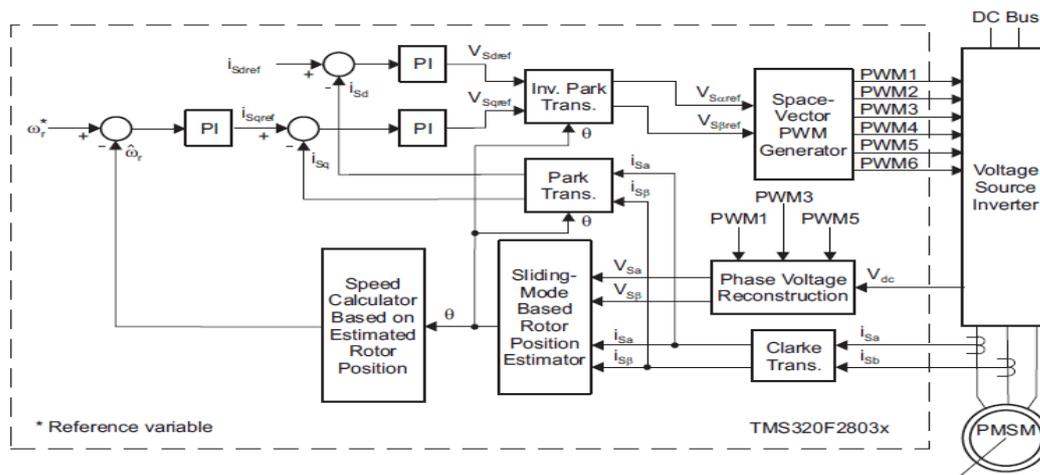


Fig. 3 Block Diagram

#### B. Space Vector Pulse Width Modulation (SVPWM)

SVPWM was control technique widely used in power electronic equipment control. Idea of the method was to create a continuous shift of the space vector equivalent of the voltage vector of inverter on the circle orbit .With the steady shift of the space vector on a circular orbit, the higher harmonics (noise) was removed and the relationship between control signal and output voltage amplitude became linear. In this article, the SVPWM technique was used in the creation of vector to control the inverter using IGBT power switches

It is a special switching scheme of a 3-phase power converter with the six power transistors. According to the ON/OFF switching of upper transistors in 3-phase power converter, there have eight possible combinations. The eight vectors are called basic space vectors and they are denoted by  $U_0, U_{60}, U_{120}, U_{180}, U_{240}, U_{300}, O_{000}$  and  $O_{111}$ , which are shown in Fig. 2. Using the *Clarke* transformation, the project values in  $\alpha$ - $\beta$  axis for six basic space vectors can be obtained. The SVPWM technique is applied to approximate the reference voltage  $U_{out}$ , and it combines the switching pattern with the basic space vectors. Therefore, if the motor-voltage vector  $U_{out}$  locates at one of the six sectors ( $S_3, S_1, S_5, S_4, S_6, S_2$ ) at any given time, it can be approximated by the vector sum of two vector components lying on the two adjacent basic vectors.

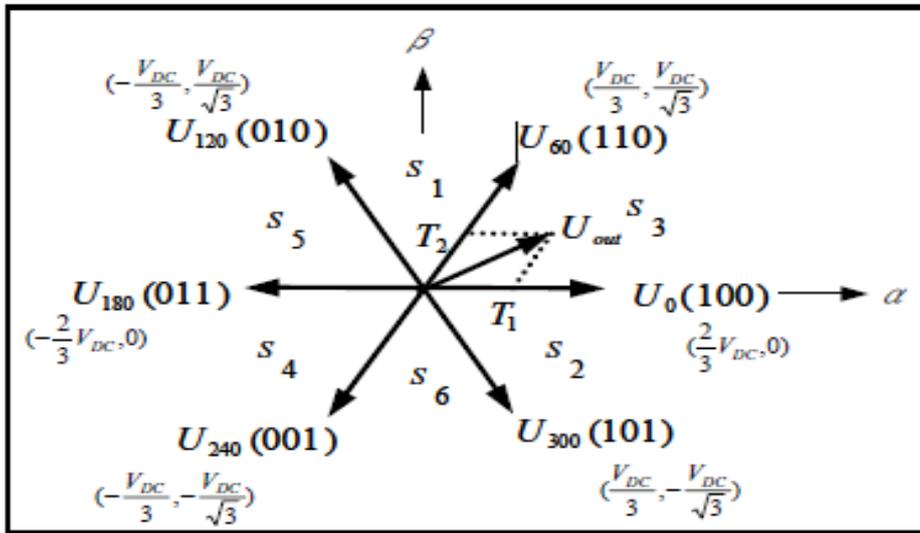


Fig. 4 Basic vector space and switching patterns

#### IV. Results and Observations

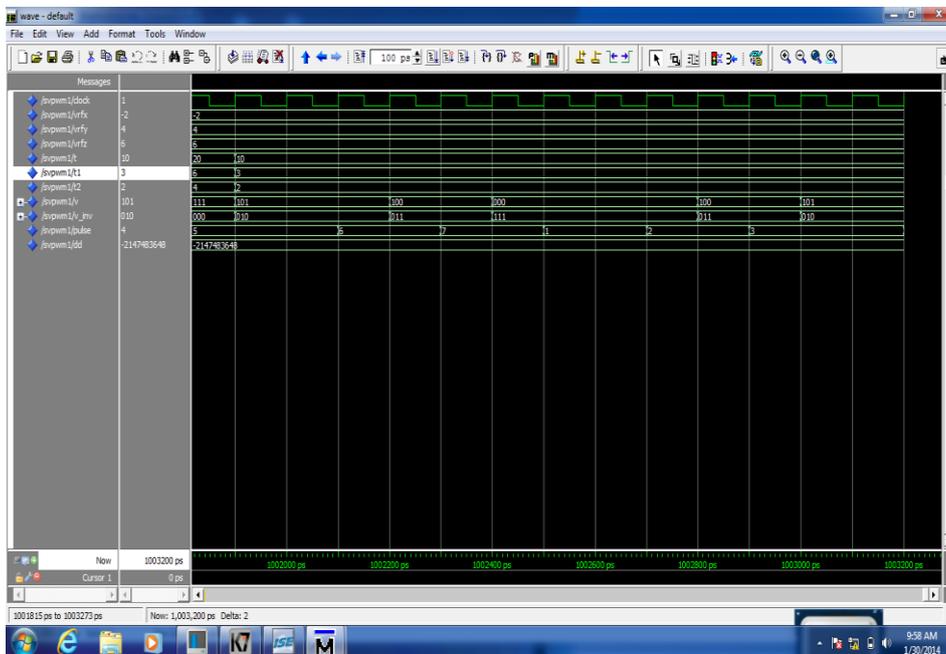


Fig. 5 Waveform for Proposed System

### A. Waveforms for Proposed System

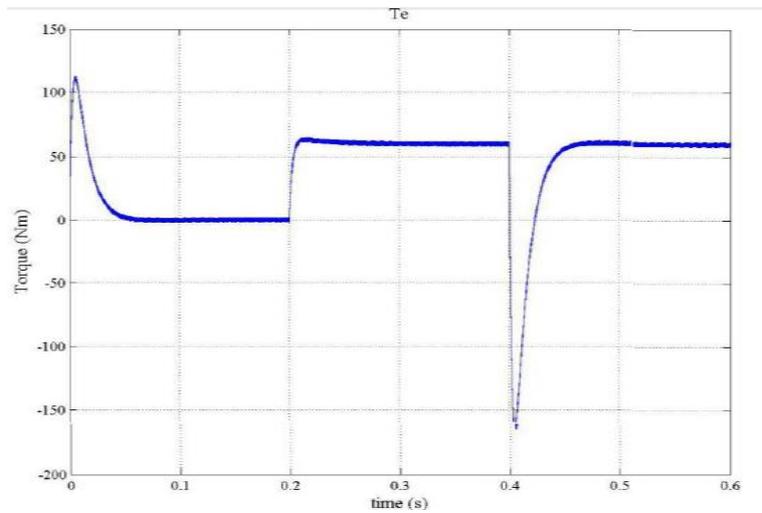


Fig. 6 Torque Dynamic Response

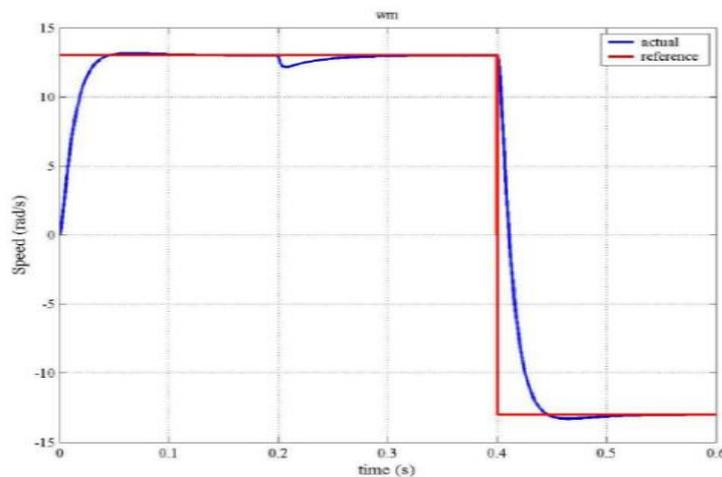


Fig. 7 Speed Dynamic Response

### V. Conclusion and Future Work

Permanent Magnet Synchronous Motors have become more popular in the last years. The main reasons of that popularity are their durability, high efficiency and high power factor rates. The main advantage is that Independently Control of Torque and Speed can be achieved by using the Field Oriented Control where two currents responsible for Torque and Field are separately resolved and controlled. Thus the Proposed method was designed and was found to be more efficient than the Existing method in terms of the control strategies used

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