**MASTER CORO M2**
**MASTER IN CONTROL AND ROBOTICS**

# STATOR FLUX ORIENTED CONTROL OF EH/HEV MOTOR DRIVES

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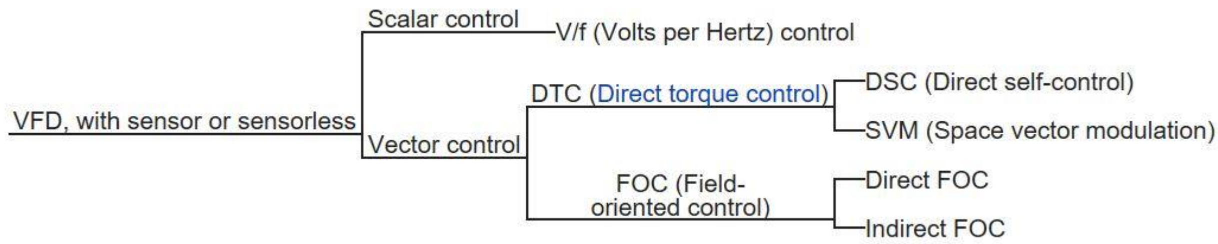
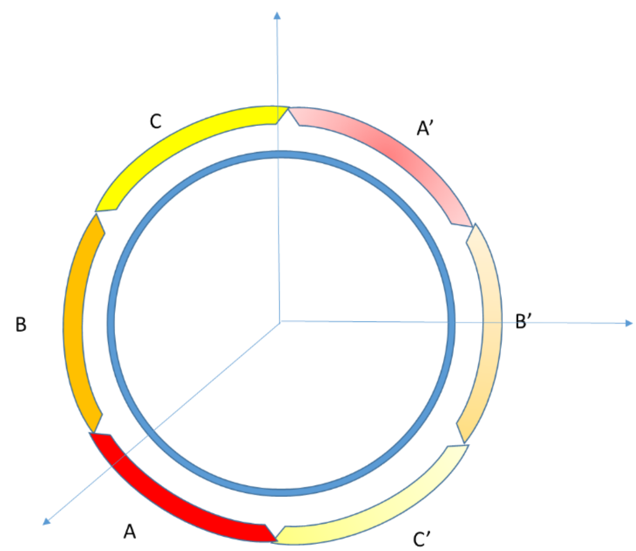
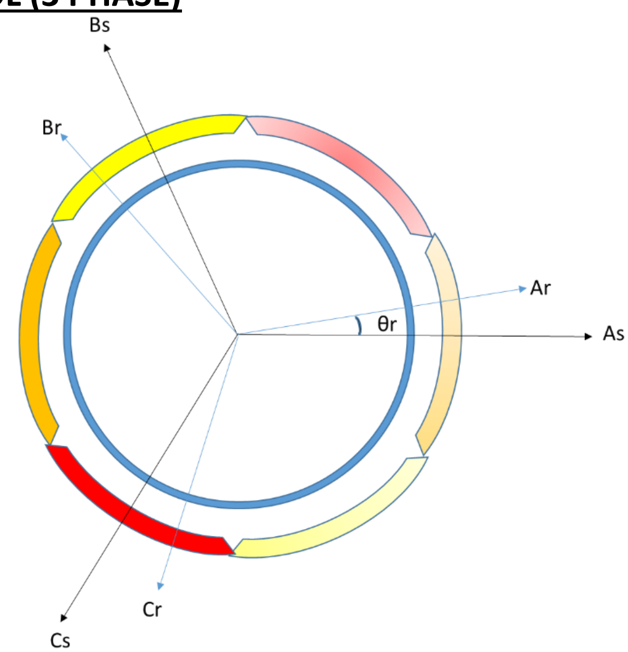
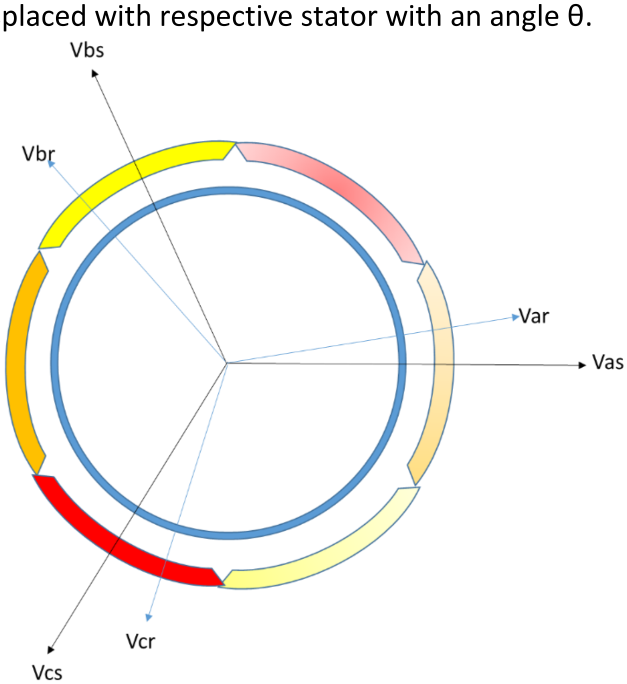


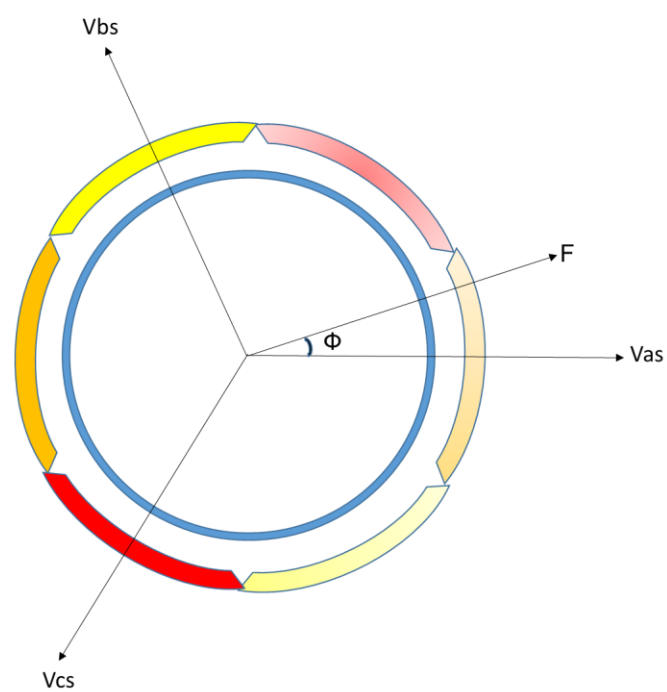

## INTRODUCTION TO FIELD ORIENTED CONTROL (3 PHASE)



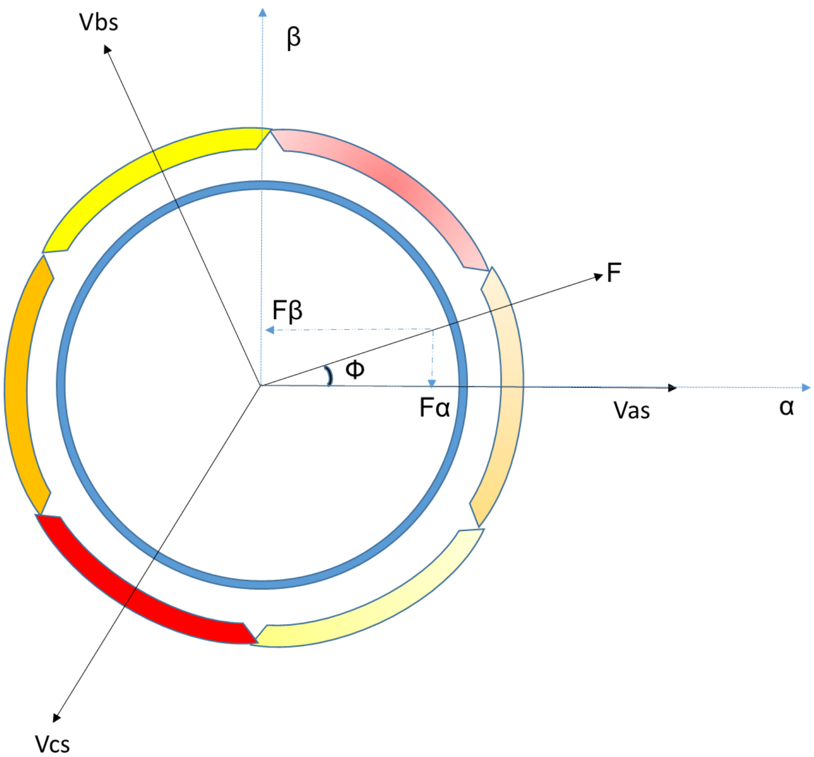

3 Phase of rotor and stator vectors can be visualized as in above vector orientation, Θr- Rotor is displaced with respective stator with an angle θ.



The above vectors describe the 3 phase stator and rotor vectors. F – resultant mmf of three phases of stator at constant amplitude (space vector) making an angle α.

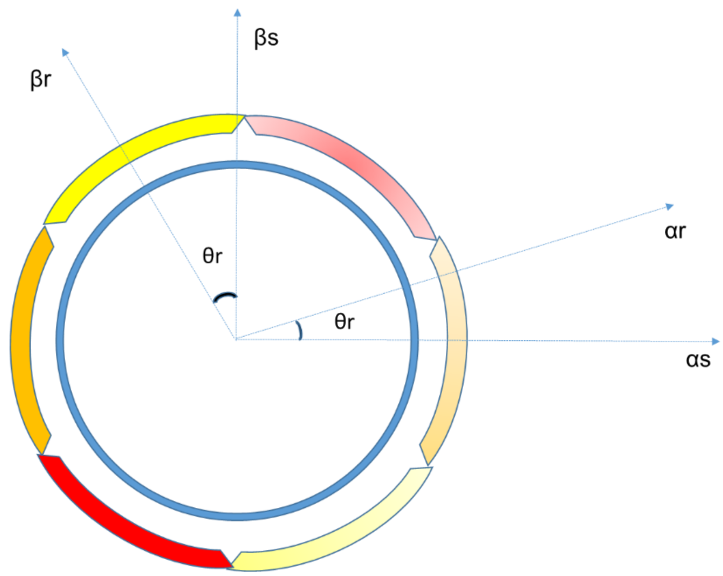
## THE CLARKE TRANSFORMATION




F has α and β component, which represents currents in all phases. This is for stator field, similarly for rotor field, in below figures.

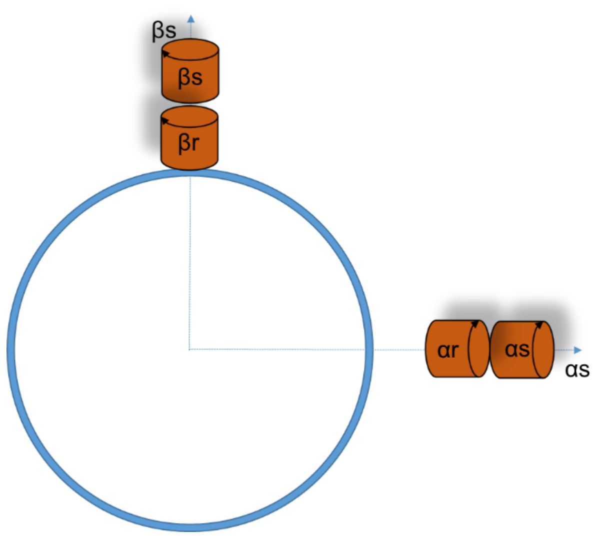
$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

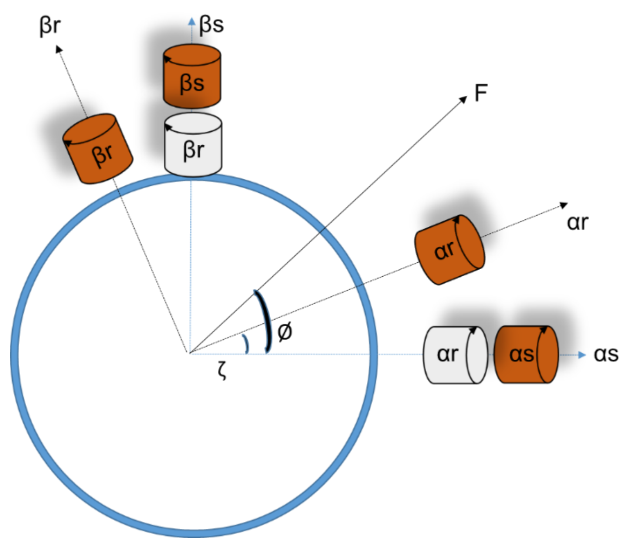
$$N_{\alpha\beta} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = Ns. \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$




αs and βs are fixed in space with 90degrees so, there is no flux linkage between them, but αr and βr are rotating and there would be a flux linkage between stator and rotor coils.

When we have any excitations in αs axis and αr axis, the angle between the two axis is going to change continuously with respect to time as rotor rotates and therefore the mutual inductance between them are bound to change continuously one can't avoid that at all. One can avoid the description of the angle and have independent of rotor angle and time when all these coils are fixed with respective each other. When all the coils are fixed the inductance is also fixed.




The net mmf at an angle Ø due to rotor coil αr and βr is equivalent to the mmf due a rotor if present on stator axis.

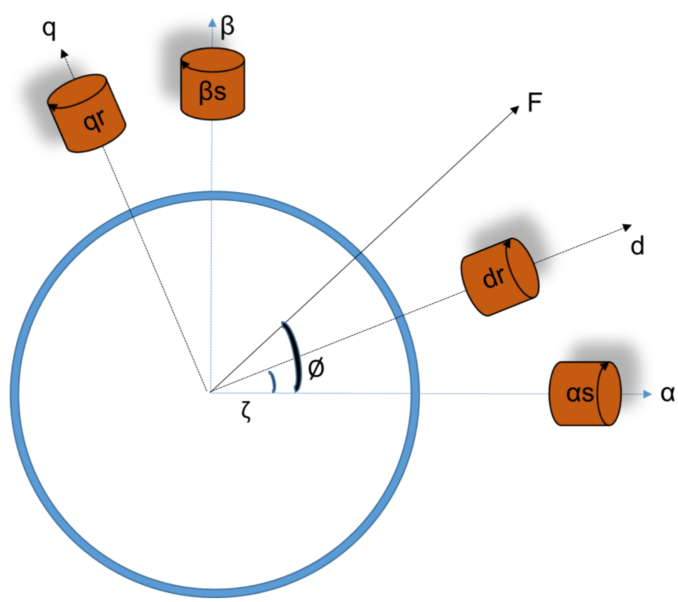
$$\mathbf{F} = N[(i_{\alpha r}.cos(\theta)_r - i_{\beta r}.sin(\theta)_r)cos\phi + (i_{\alpha r}.sin(\theta)_r - i_{\beta r}.cos(\theta)_r)sin\phi]$$

So now rotor coils are placed along the stator α and β axis. Now coils of stator and rotor are fixed with respective each other. Mmf generated by rotor axis at any instance of angle with respect to stator can be mapped to mmf generated when the coils are fixed along the stator axis. This frame is called a stationary reference frame. In fact, these coils are not rotor coils, these are called pseudo stationary coils, which provide the same result as the rotor axis once placed with an angle with respective stator axis.

## THE PARK TRANSFORMATION (ARBITRARY REFERENCE FRAME (D,Q))

The speed of arbitrary reference frame can be anything, we can fix the speed of reference frame to zero, which is then called stationary reference frame and d axis is aligned with stator A phase axis. We can fix the reference frame speed to a speed which is different from the rotor axis speed, in this case it's called synchronous reference frame. In the rotor rotating frame, speed is equivalent to rotor speed.

Now assuming there is no pseudo stationary coils of rotor on stator axis, and we need to calculate the flux produced at an angle Ø from the stator axis and we superimpose d,q reference frame on this axis, 90 degrees in between them and angle ζ between stator axis and d axis .




Now assuming only stator coil. What is the mmf at an angle Ø. We can also derive equations for the same in terms of rotor coils. The current applied on the d,q axis are now independent of time.

$$F(\phi) = N_{\alpha\beta}[i_d.cos(\phi - \delta) + i_q.sin(\phi - \delta)]$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos(\delta) & sin(\delta) \\ -sin(\delta) & cos(\delta) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

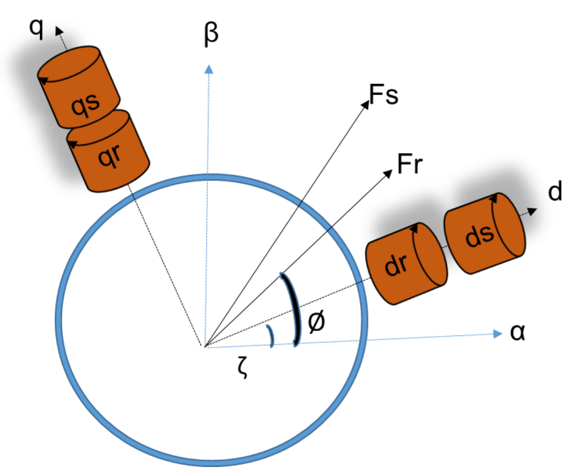
$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos(\delta) & sin(\delta) \\ -sin(\delta) & cos(\delta) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} cos(\delta) & sin(\delta) & 0 & 0 & 0 & 0 \\ -sin(\delta) & cos(\delta) & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & cos(\delta) & sin(\delta) & 0 \\ 0 & 0 & 0 & -sin(\delta) & cos(\delta) & 0 \end{bmatrix} \begin{bmatrix} V_{\alpha s} \\ V_{\beta s} \\ V_{\alpha r} \\ V_{\beta r} \end{bmatrix}$$

$$\Psi_{ds} = L_{ss} i_{ds} + L_m i_{dsr}$$
$$\Psi_{qs} = L_{ss} i_{qs} + L_m i_{qsr}$$
$$\Psi_{dr} = L_{rr} i_{dr} + L_m i_{drr}$$
$$\Psi_{qr} = L_{rr} i_{qs} + L_m i_{drr}$$

Producing resultant Flux of rotor and stator axis in d,q frame

In a stationary frame, suppose d axis is placed along the rotor flux vector, with an angle ζ, we can achieve the independent control of Torque with the q axis and flux with the d axis, but for which we must know the rotor position. This type of approach is called the rotor field orientation control and if d axis is placed along the stator flux vector, estimating the stator vector, this approach is called stator filed orientation control.



$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} r_s + \sigma L_{ss} p & -\omega_s \sigma L_{ss} & L_m p / L_{rr} & -L_m / L_{rr} \omega_s \\ \omega_s \sigma L_{ss} & r_s + L_{ss} p & -L_m / L_{rr} \omega_s & L_m p / L_{rr} \\ -r_r L_m / L_{rr} & 0 & r_r / L_{rr} + p & -(\omega_s - \omega_r) \\ 0 & -r_r L_m / L_{rr} & (\omega_s - \omega_r) & r_r / L_{rr} + p \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{ds} \\ \psi_{qs} \end{bmatrix}$$

If torque is given as:

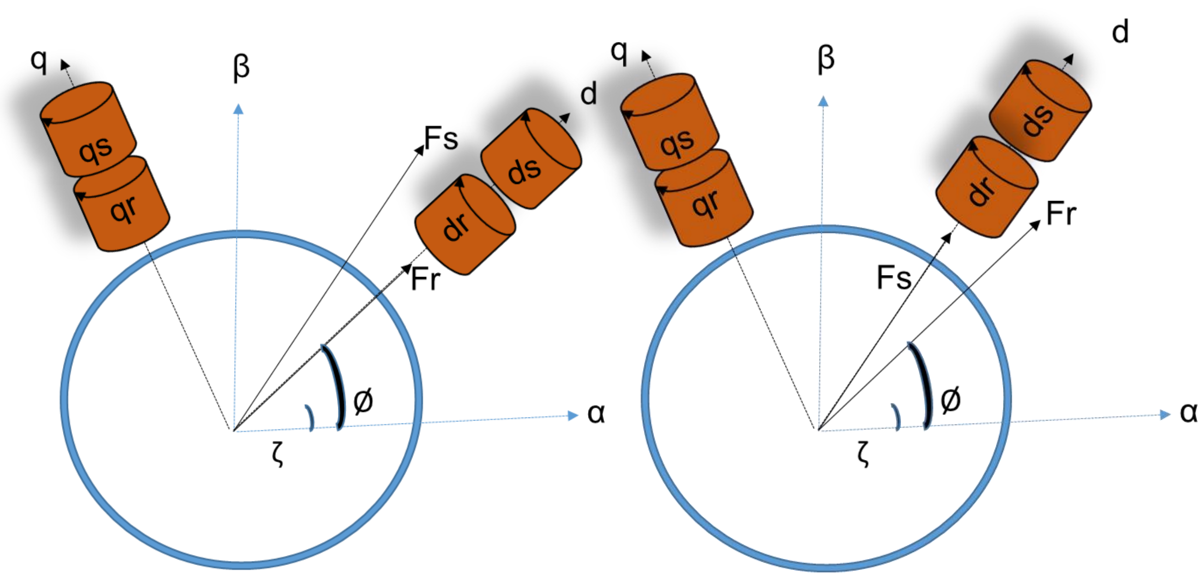
$$T = L_m / L_{rr} (i_{qs} \psi_{dr} - i_{ds} \psi_{qr})$$

Now placing the d axis along the rotor flux axis, gives no component of flux along the q axis, so now the torque is expressed as:

$$T = L_m / L_{rr} (i_{qs} \psi_{dr})$$

$$\psi_s = R_r L_m / L_{rr} . i_d / (p + R_r / L_{rr})$$

D axis is placed along stator or rotor for different field oriented control.



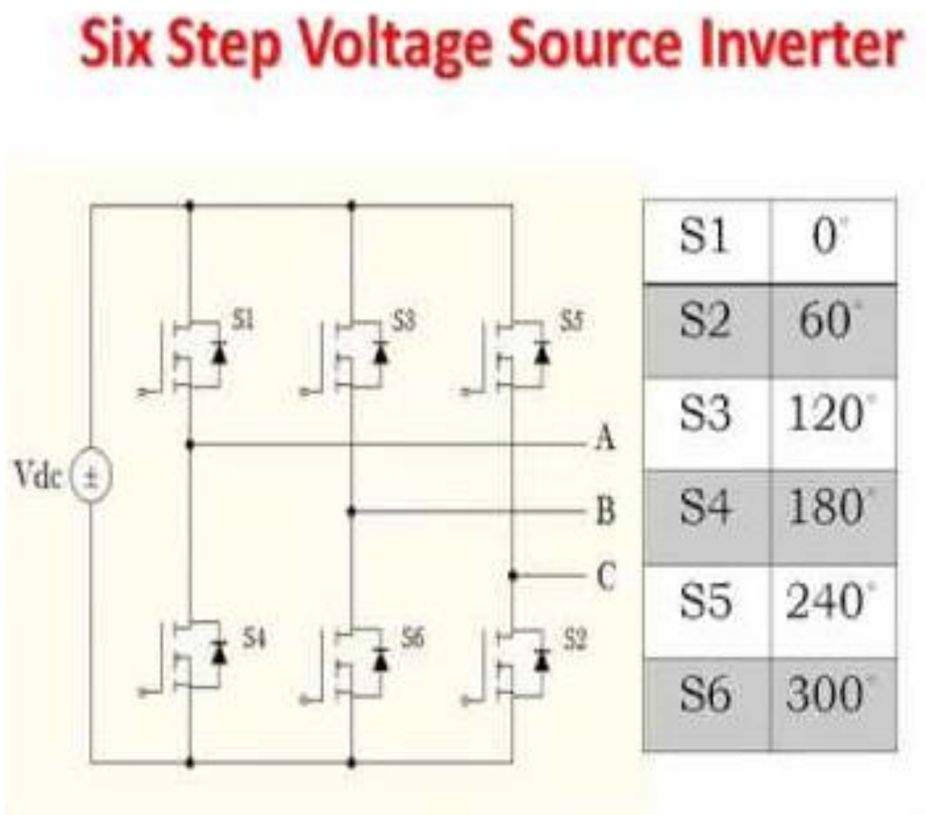

ROTOR FLUX ORIENTED CONTROL

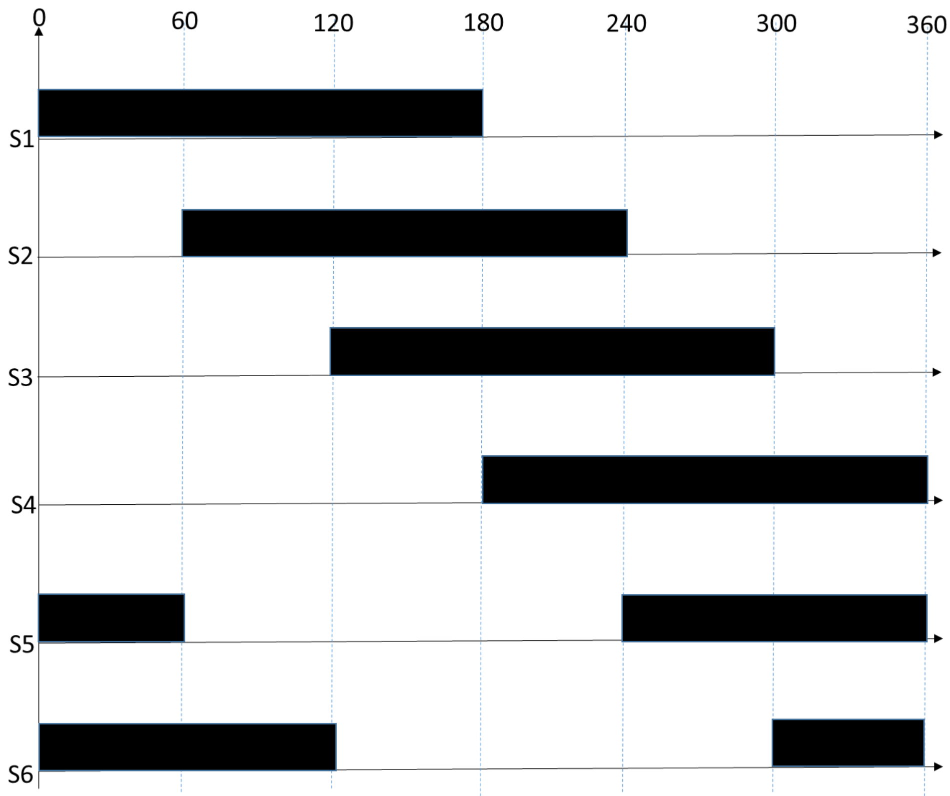
STATOR FLUX ORIENTED CONTROL

Vector control, also called field-oriented control (FOC), is a variable-frequency drive (VFD) control method in which the stator currents of a three-phase AC electric motor are identified as two orthogonal components that can be visualized with a vector. One component defines the magnetic flux of the motor, the other the torque. The control system of the drive calculates the corresponding current component references from the flux and torque references given by the drive's speed control. Typically, proportional-integral (PI) controllers are used to keep the measured current components at their reference values. The pulse-width modulation of the variable-frequency drive defines the transistor switching according to the stator voltage references that are the output of the PI current controllers.

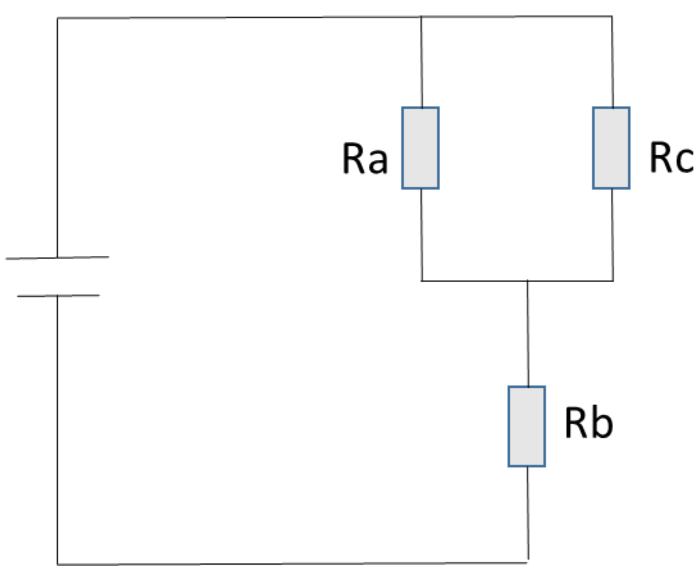
## PULSE WIDTH MODULATION

We have a 3 phase AC induction motor. So, we need to convert a DC signal into AC signal. For this we use a 3 phase voltage inverter. In an inverter (six step inverter) or six bidirectional switches, each switch beginning at different angle. 3 phase with bidirectional switches generates 8 different combinations of switching sequence. The below shown table is switching for 3 phase. From the above table we can say that if we want an A phase positive voltage, we need to switch S1 on and for negative voltage, switch off S1 and switch on S4. If we have both switch on, thus making a loop, and generates nothing. Similarly, for other phases.






At any instance at least 3 switched will be on state.




Ra=Rb=Rc=R

Vb = Ib*Rb

Ib = Vdc/Rt

Rt = 3R/2

Vb = 2/3 Vdc

Va = Vc = ?

Va = Vdc – 2/3Vdc

Va = Vc = Vdc/3

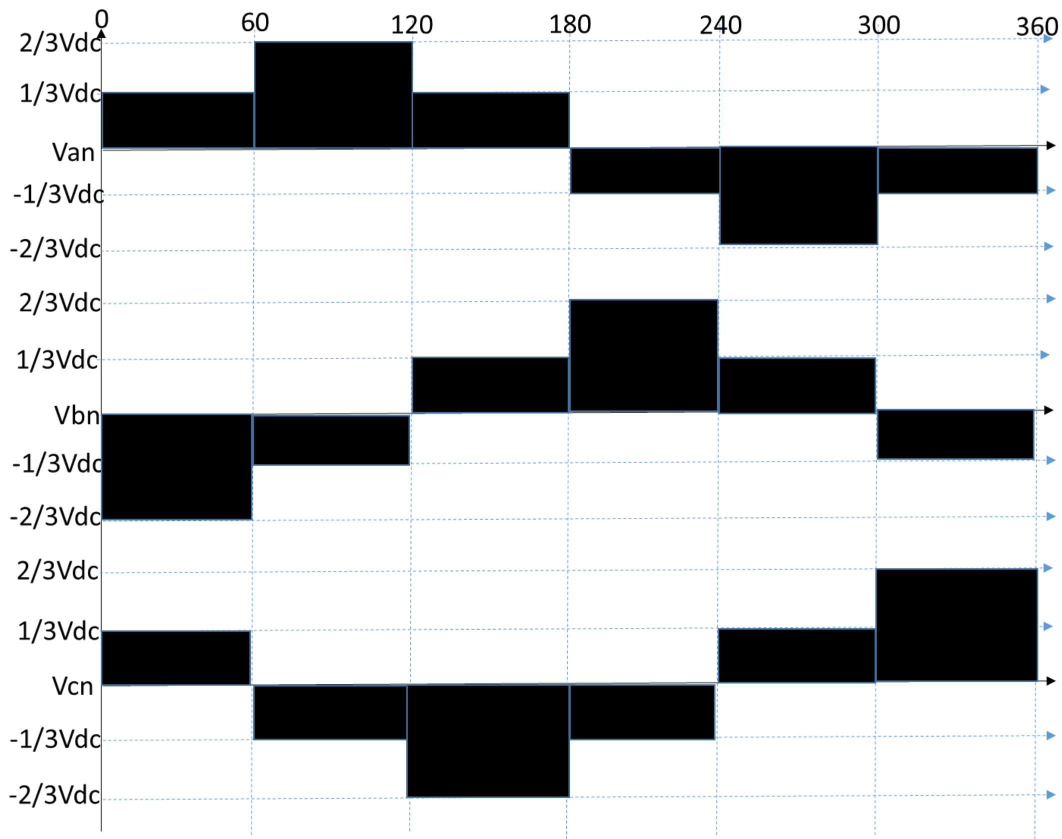


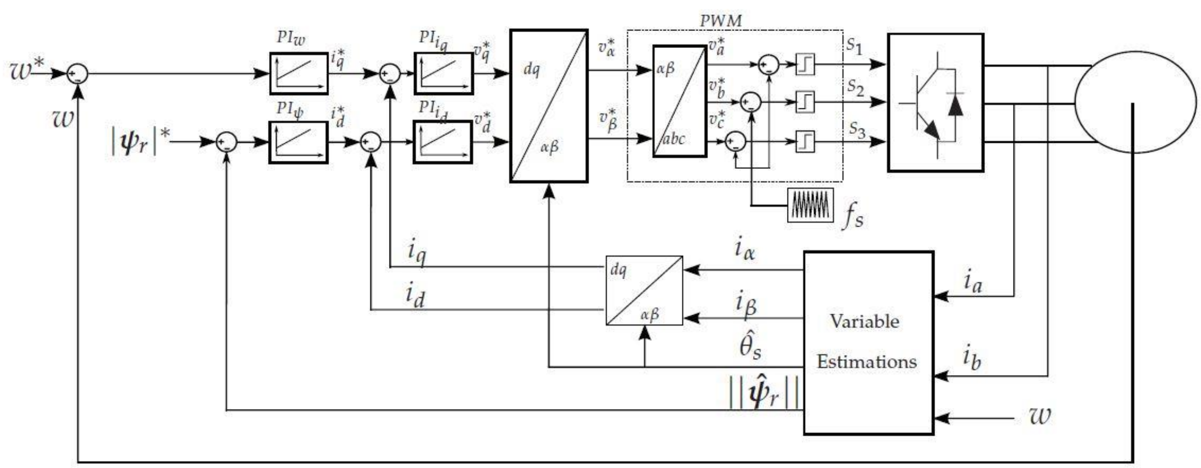

Table:1 Phase voltage values for different switching state

| State | Switch ON | $V_A$ | $V_B$ | $V_C$ |
|---|---|---|---|---|
| 1 | 1,4,6 | (2/3)Vdc | -(1/3) Vdc | -(1/3) Vdc |
| 2 | 1,3,6 | (1/3) Vdc | (1/3) Vdc | -(2/3)Vdc |
| 3 | 2,3,6 | -(1/3) Vdc | (2/3)Vdc | -(1/3) Vdc |
| 4 | 2,3,5 | -(2/3)Vdc | (1/3) Vdc | (1/3) Vdc |
| 5 | 2,4,5 | -(1/3) Vdc | -(1/3) Vdc | (2/3)Vdc |
| 6 | 1,4,5 | (1/3) Vdc | -(2/3)Vdc | (1/3) Vdc |
| 7 &0 | 1,3,5 & 2,4,6 | 0 | 0 | 0 |

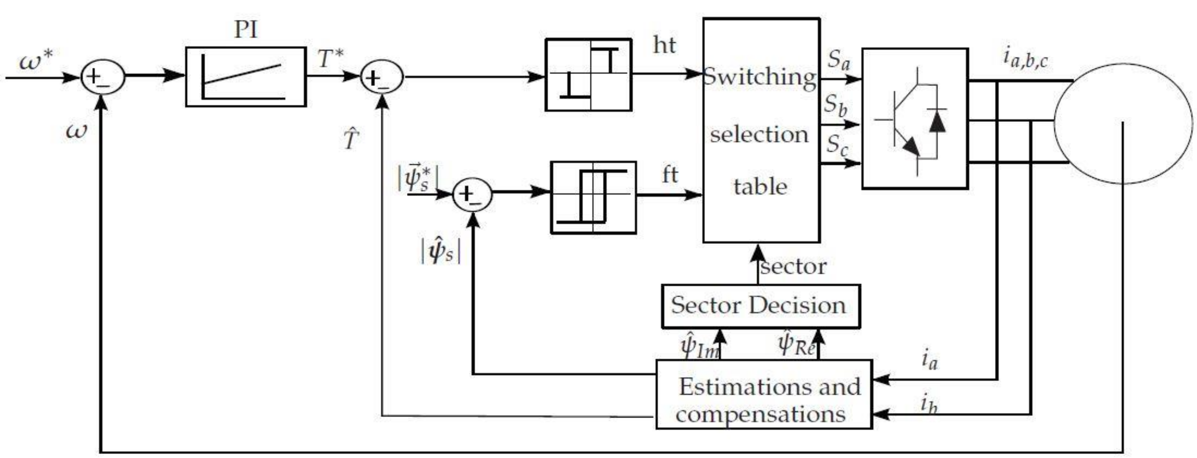
## SPACE VECTOR MODULATION

State 1 to 6 are called active vectors, state 7 and 8 are zero vectors. If you transform three phase sinusoidal signal into the space vector domain, it is basically a revolving voltage vector. Considering an electric drive system, the controller generates a reference voltage, Vs, represented with voltage space vector.

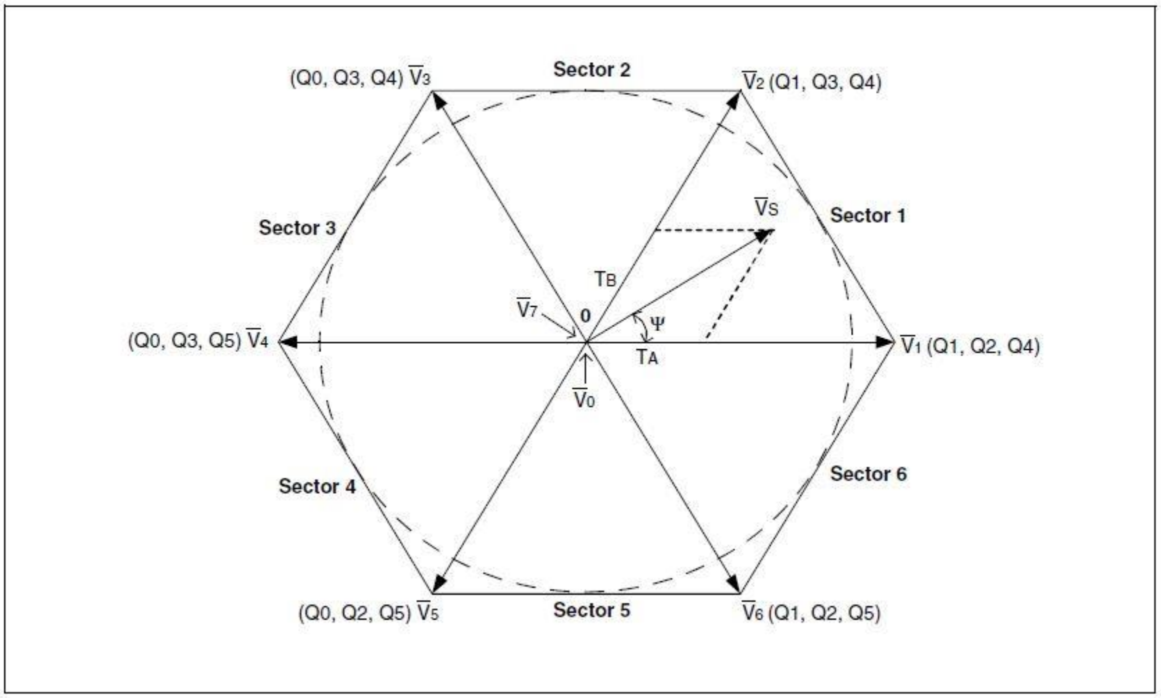
In order to apply this voltage on the motor, it is required to convert this reference voltage to the switching signals for the inverter. To do this, several PWM strategies are available. In the sub-oscillation methods, the three phase voltages are firstly calculated and they are compared with a high frequency carrier signal to generate the pulses to control the inverter switches. Besides such methods, it is possible to generate the switching signals directly using the space vector of the reference voltage, without having to convert the space vector to the three phase values at first. This method is called space vector modulation (SVM).

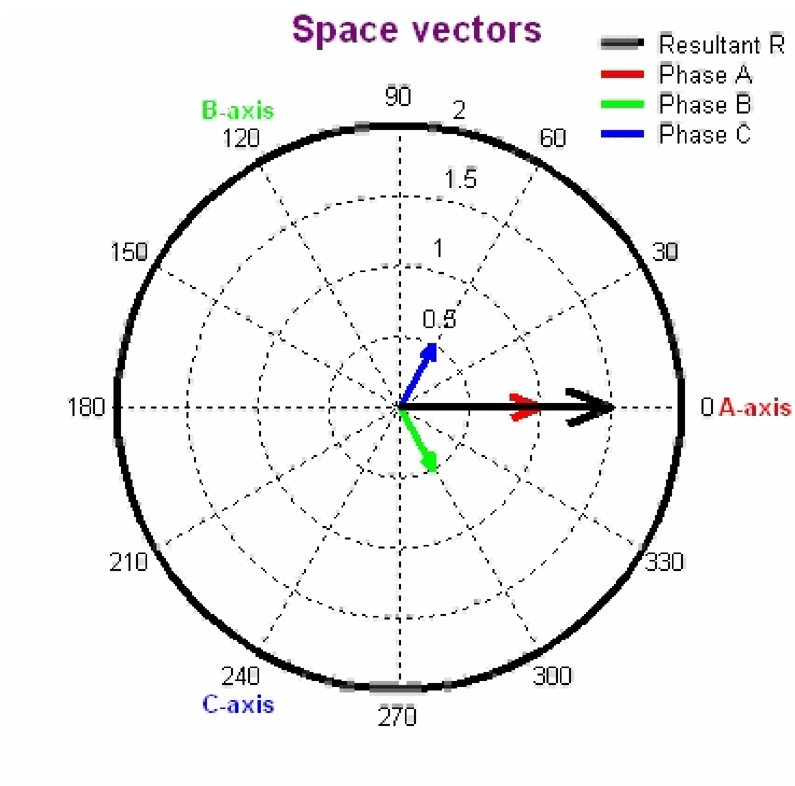



(**a**) Block diagram: FOC.




(**b**) Block diagram: DTC.



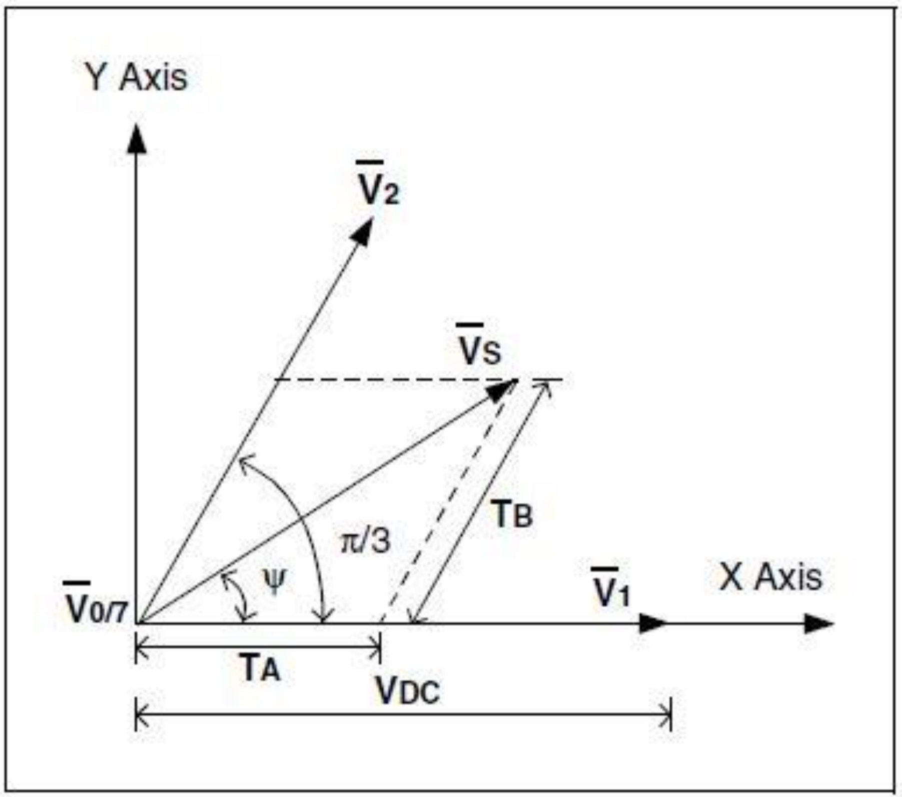

$\overline{Vref}$ = 2/3(Va + a*Vb + a^2*Vc) where, a = e^(j*2*pi/3). The magnitude of reference vector is sqrt(V α^2 +V β^2). The phase angle is evaluated from θ = arctan(V β/ V α).

Suppose a reference voltage Vs is to be applied to the motor. If Vs is not identical to one of the base vectors, it must be approximated using these eight vectors. In the case shown in Figure below, Vs can be approximated based on timely switching among V1, V2 and the two zero vectors. In this case, vector V2 should be applied for a longer time than V1 since Vs is nearer to V2 and a time of zero vectors should also be applied in order to reduce the magnitude.

Supposing the reference voltage space vector us falls between two adjacent base vectors, V1 and V2, the reference vector Vs can be represented with the combination of the two vectors, V1 and V2. Sampling time is given as Ts = 1/Fpwm. T0,T1….T7 are on time for corresponding states. We have some general equations,

$$\overline{V}s = \left(\frac{T0}{Ts} \times \overline{V}0\right) + \left(\frac{T1}{Ts} \times \overline{V}1\right) + \left(\frac{T2}{Ts} \times \overline{V}2\right) + \left(\frac{T3}{Ts} \times \overline{V}3\right) + \left(\frac{T4}{Ts} \times \overline{V}4\right) + \left(\frac{T5}{Ts} \times \overline{V}5\right) + \left(\frac{T6}{Ts} \times \overline{V}6\right) + \left(\frac{T7}{Ts} \times \overline{V}7\right)$$

$$Ts = T0 + T1 + T2 + T3 + T4 + T5 + T6 + T7$$




It is assumed that Vs remains steady during Ts period.

$$\overline{V}s = \left(\frac{TA}{Ts} \times \overline{V}1\right) + \left(\frac{TB}{Ts} \times \overline{V}2\right) + \left(\frac{T0/7}{Ts} \times \overline{V}0/7\right)$$

The above equation means that the state 1 is in active state for Ta time and it is in active state 2 for Tb time. For the remaining time of Ts, no voltage is applied. This can be achieved by applying inactive state 0 (or 7) for the remaining time T0 (or T7). Sampling time for this section is given as,

$$\boxed{T_S = T_A + T_B + T_{0/7}}$$

The time intervals, TA, TB and T0/7, have to be calculated such that the average volt seconds produced by the vectors, V1, V2 and V0/7 along the X and Y axes, are the same as those produced by the desired reference space vector VS. The modulation index or amplitude ratio is defined as:

$$m = \frac{|\nabla_S|}{V_{DC}}$$

Modulation index is the ratio of peak magnitudes of the modulating waveform and the carrier waveform. It relates the inverter’s dc-link voltage and the magnitude of pole voltage (fundamental component) output by the inverter. where |VS| is the amplitude or the length of VS. Resolving VS along the X and Y axes, we get

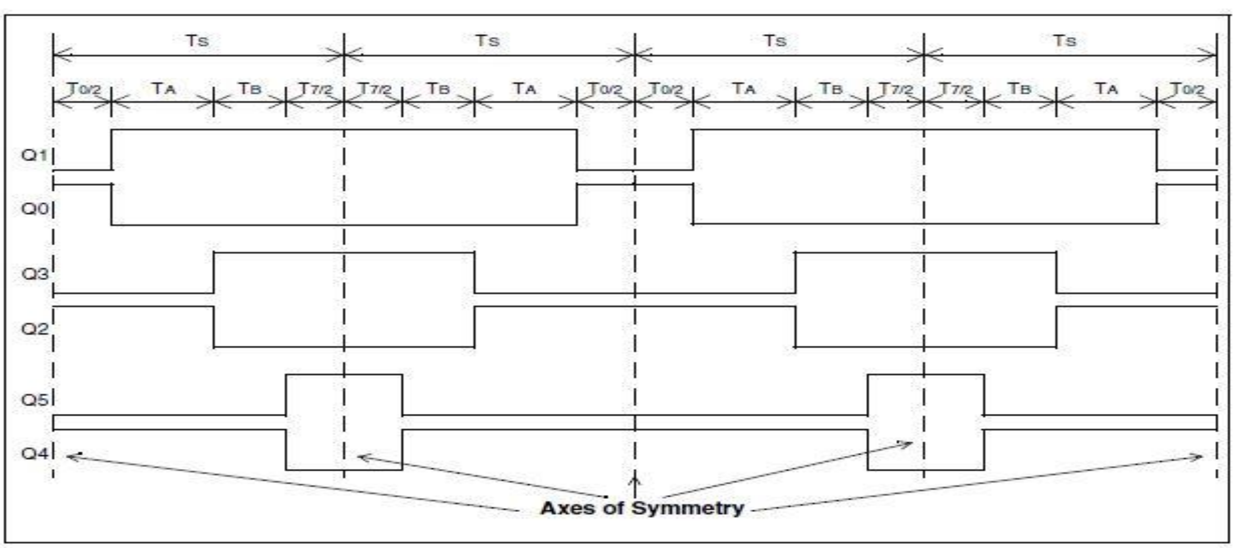
$$(V_{DC} \times T_A) + (V_{DC} \times \cos\pi/3 \times T_B) = |\nabla_S| \times \cos\psi \times T_S$$
and
$$V_{DC} \times \sin\pi/3 \times T_B = |\nabla_S| \times \sin\psi \times T_S$$

Solving for TA and TB, we get:

$$\frac{T_A}{T_S} = \frac{2}{\sqrt{3}} \times m \times \sin\left(\frac{\pi}{3} - \psi\right)$$
$$\frac{T_B}{T_S} = \frac{2}{\sqrt{3}} \times m \times \sin\psi$$

T0 can be found from the above equations

T0 (or T7) is split into two and then applied at the beginning and at the end of the TS. The typical VSI switching waveforms in below figure.



These symmetries are mainly responsible for having lower THD in SVM compared to Sine PWM in the linear operating region. It is clear that in the linear operating region, the maximum line-to-line voltage amplitude can be achieved when VS is rotated along the largest inscribed circle in the space vector hexagon. In mathematical terms, this is equivalent to:

$$m_{max} = \frac{\text{Radius of Largest Inscribed Circle}}{V_{DC}}$$

$$m_{max} = \frac{V_{DC} \times \cos\pi/6}{V_{DC}} = \cos\pi/6 = \frac{\sqrt{3}}{2}$$

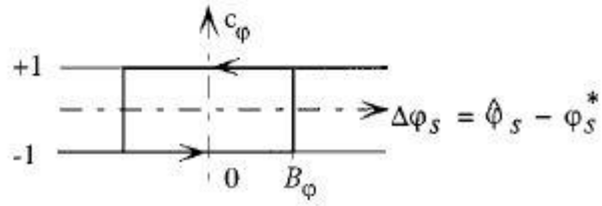
$$\begin{aligned}&\text{Maximum Line-to-Line Voltage}\\ &= \frac{2}{\sqrt{3}} \times m_{max} \times V_{DC}\\ &= \frac{2}{\sqrt{3}} \times \frac{\sqrt{3}}{2} \times V_{DC} = V_{DC}\end{aligned}$$

Equation above shows that it is possible to get line-to-line voltage amplitude as high as VDC using the SVM algorithm in the linear operating range. This is the main advantage of the SVM algorithm when compared to the Sine PWM algorithm. Due to higher line-to-line voltage amplitude, the torque generated by the motor is higher. This results in better dynamic response of the motor.

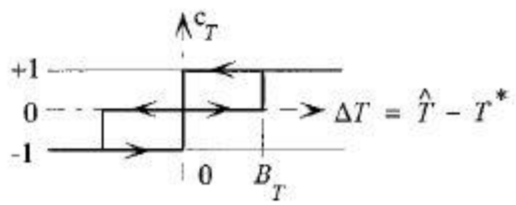
| | Voltage in Volts | Frequency in Hertz | Modulation Index | THD of Stator Currents |
|---|---|---|---|---|
| Phase a | 400 | 50 | 0.8 | 0.49% |
| Phase b | 400 | 50 | 0.8 | 0.48% |
| Phase c | 400 | 50 | 0.8 | 0.47% |

## DISCRETE SPACE VECTOR MODULATION

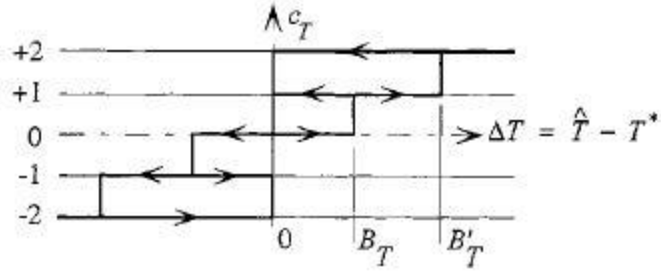
The possibility to compensate, at each sampling period, the torque and flux errors is strongly dependent on the number of available voltage vectors. A high number of voltage vectors can be generated using nontraditional power circuit topology as proposed.

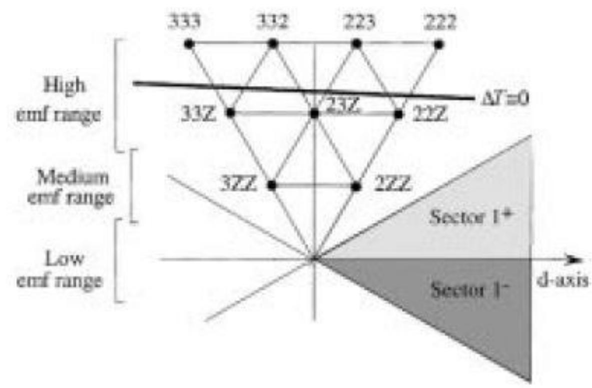



Flux hysteresis comparator.




Torque hysteresis comparator.




The number of voltage vectors which can be generated is directly related to the number of time intervals by which the sampling period is subdivided. Higher the number of voltage vectors lower the amplitude of current and torque ripple. However, a high number of voltage vectors requires the definition of new and more complex switching tables. A good solution should be defined as a compromise between a good ripple compensation and the complexity of the voltage vector selection strategy.

## DIFFERENCE BETWEEN DFOC AND IFOC

The vector control technique decouples the two components of stator current space vector: one providing the control of flux and the other providing the control of torque. Thirteen years later, a new technique for the torque control of induction motors was developed and presented by I.Takahashi as direct torque control (DTC) and by M. Depenbrock as direct self-control (DSC). Since the beginning, the new technique was characterized by simplicity, good performance and robustness. Using DTC or DSC it is possible to obtain a good dynamic control of the torque without any mechanical transducers on the machine shaft. Thus, DTC and DSC can be considered as “sensor less type” control techniques. The basic scheme of DSC is preferable in the high power range applications. The electromagnetic torque is proportional to the product of field flux and armature current. Field flux is proportional to the field current and is unaffected by the armature current because of orthogonal orientation between armature mmf and field mmf. Therefore, in a separately excited DC machine, with a constant value of field flux the torque Is directly proportional to the armature current. The name direct torque control is derived by the fact that, on the basis of the errors between the reference and the estimated values of torque and flux, it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits. Unlike FOC, DTC does not require any current regulator, coordinate transformation and PWM signals generator (as a consequence timers are not required). In spite of its simplicity, DTC allows a good torque control in steady state and transient operating conditions to be obtained. The problem is to quantify how good the torque control is with respect to FOC. In addition, this controller is very little sensible to the parameters detuning in comparison with FOC.

On the other hand, it is well known that DTC presents some disadvantages that can be summarized in the following points:

1) difficulty to control torque and flux at very low speed;

2) high current and torque ripple;

3) variable switching frequency behavior;

4) high noise level at low speed;

5) lack of direct current control.

There are two fundamental directions for the induction motor control: • Analogue: direct measurement of the machine parameters (mainly the rotor speed), which are compared to the reference signals through closed control loops; • Digital: estimation of the machine parameters in the sensor less control schemes (without measuring the rotor speed), with the following implementation methodologies:

• Slip frequency calculation method;

• Speed estimation using state equation;

• Estimation based on slot space harmonic voltages;

• Flux estimation and flux vector control;

• Direct control of torque and flux;

• Observer-based speed sensor less control;

• Model reference adaptive systems;

• Kalman filtering techniques;

• Sensor less control with parameter adaptation;

• Neural network based sensor less control;

• Fuzzy-logic based sensor less control.

“FOC has been solely developed for high-performance motor applications which can operate smoothly over the wide speed range, can produce full torque at zero speed, and is capable of quick acceleration and deceleration”.

If the field angle is calculated by using terminal voltages and currents or flux sensing windings and rotor speed, then it is known as direct FOC. The field angle can also be obtained by using rotor position measurement and slip position by partial estimation with only machine parameters but not any other variables such as voltages or currents, this class of control scheme is known as indirect FOC. The rotor field angle is obtained by submission of rotor speed and slip frequency.

An important requirement to obtain good control performance is to make the motor parameters in the field-oriented controller coincide with the actual parameters of the motor. The ability to inject currents into the motor with a current source opened up new possibilities for parameter determination. It was Takayoshi who described a new identification technique utilizing injected negative sequence components. It is shown that the stator as well as rotor resistance and leakage inductance can be determined on line while the motor is driving the load. The theory is verified with a full-scale hybrid computer simulation of a field-oriented controlled PWM inverter based induction motor drive.

In direct FOC the rotor angle or control vector is obtained by the terminal voltages & currents directly by using flux estimators. The direct vector control is also known as feedback vector control scheme. Similar to Indirect Vector Control, various controllers have been implemented on direct vector controlled induction motor drives also to improve the performance of the drive. While the direct method is inherently the most desirable control scheme, it suffers from high cost and the unreliability of the flux measurement. Although the indirect method can approach the performance of the direct measurement scheme, the major weakness of this approach is centered upon the accuracy of the control gains which, in turn, depend heavily on the motor parameters assumed in the feed forward control algorithm.

The direct FOC determines the orientation of the air-gap flux by use of a hall-effect sensor, search coil or other measurement techniques. However, using sensors is expensive because special modifications of the motor are required for placing the flux sensors. Furthermore, it is not possible to directly sense the rotor flux. Calculating the rotor flux from a directly sensed signal may result in inaccuracies at low speed due to the dominance of stator resistance voltage drop in the stator voltage equation and inaccuracies due to variations on flux level and temperature. In FOC, to perform the frame transformation, accurate rotor flux position is needed to be acquired. Because with inaccurate rotor flux position torque and flux components are not be completely decoupled, as a result of which dynamic response become poor. So, knowledge of rotor flux position is the core of the FOC.

## COMPARISON WITH DIRECT VECTOR CONTROL

The major disadvantage of direct vector method is the need of so many sensors. Fixing so many sensors in a machine is a tedious work as well as costlier. Due to this the scheme is prevented from being used. Several other problems like drift because of temperature, poor flux sensing at lower speeds also persists. Due to these disadvantages and some more related ones, indirect vector control is used. In indirect vector control technique, the rotor position is calculated from the speed feedback signal of the motor. This technique eliminates most of the problems, which are associated with the flux sensors as they are absent.

## ADVANTAGES OF INDIRECT FOC

1. The sensors are eliminated.
2. The dynamic performance of the indirect vector control is better than the direct vector control.
3. The cost factor is decreased.
4. There is no drift problem as in direct vector control.

## ADVANTAGES OF FIELD ORIENTED CONTROL

1. Improved torque response.
2. Torque control at low frequencies and low speed.
3. Dynamic speed accuracy.
4. Four quadrant operation.
5. Short-term overload capability.
6. Reduction in size of motor, cost
7. Reduction in power consumption.

## ADVANTAGES, DISADVANTAGES, PERFROMANCE (DTC VS DFOC)

The performance of the two control schemes is evaluated in terms of torque and current ripple, and transient response to step variations of the torque command and steady state operating condition.

Using DTC or DSC (Direct self-control) it is possible to obtain a good dynamic control of the torque without any mechanical transducers on the machine shaft.

The basic scheme of DSC is preferable in the high power range applications, where a lower inverter switching frequency can justify higher current distortion.

Unlike FOC, DTC does not require any current regulator, coordinate transformation and PWM signals generator (as a consequence timers are not required). In spite of its simplicity, DTC allows a good torque control in steady-state and transient operating conditions to be obtained.

On the other hand, it is well known that DTC presents some disadvantages that can be summarized in the following points:

1) difficulty to control torque and flux at very low speed;

2) high current and torque ripple;

3) variable switching frequency behavior;

4) high noise level at low speed;

5) lack of direct current control.

In the last five years, many researches have been carried out to try to solve the above mentioned problems of DTC scheme. In particular, the following solutions have been developed:

1) use of improved switching tables.

2) use of comparators with and without hysteresis, at two or three levels.

3) implementation of DTC schemes for constant switching frequency operation with PWM or SVM techniques.

4) introduction of fuzzy or neuro-fuzzy techniques.

5) use of sophisticated flux estimators to improve the low speed behavior

All these contributions allow the DTC performance to be improved, but at the same time they lead to more complex schemes.

So, a crucial question is to establish which one of these new schemes might be included in “DTC family.” With reference to steady-state operating conditions, the current and torque ripple evaluated for different values of speed and torque will be analyzed. For this purpose, the three-phase rms current ripple, defined by

$$I_{\mathrm{rip,rms}} = \sqrt{\frac{1}{T}\int_0^T \left(i_{\mathrm{ripA}}^2 + i_{\mathrm{ripB}}^2 + i_{\mathrm{ripC}}^2\right) dt}$$

will be calculated in a period of the fundamental current component.

With reference to transient operating conditions, the time response to a step variation of the torque command will be analyzed at different rotor speeds.

In order to fairly compare the two solutions, the following conditions have been considered as constraints:

1) the same DSP board for implementing DFOC and DTC schemes;

2) the same average switching frequency of the inverter.

Related to this last point, the comparison carried out with the same cycle period is not fair enough. This because the same cycle period does not allow a suitable use of the basic characteristics of DTC scheme, which are: easy implementation and reduced calculation time with respect to DFOC.

The same average switching frequency for the two schemes can be obtained varying the amplitude of the hysteresis bands in DTC scheme.

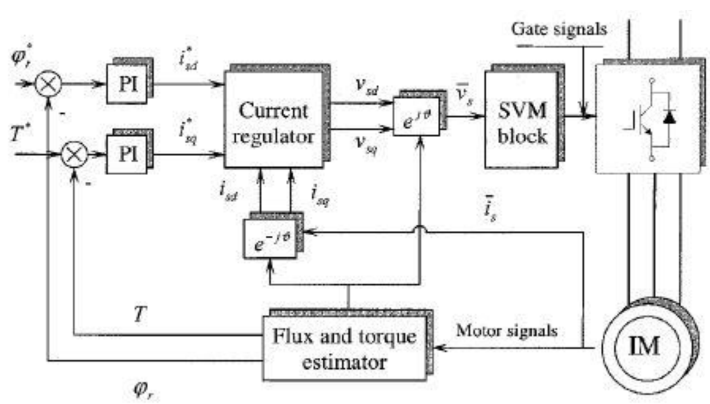



Fig. 1. Basic DFOC scheme.

Assuming a rotor flux reference frame. The current controller has been implemented in the rotor flux reference frame using PI regulators with back emf compensation.

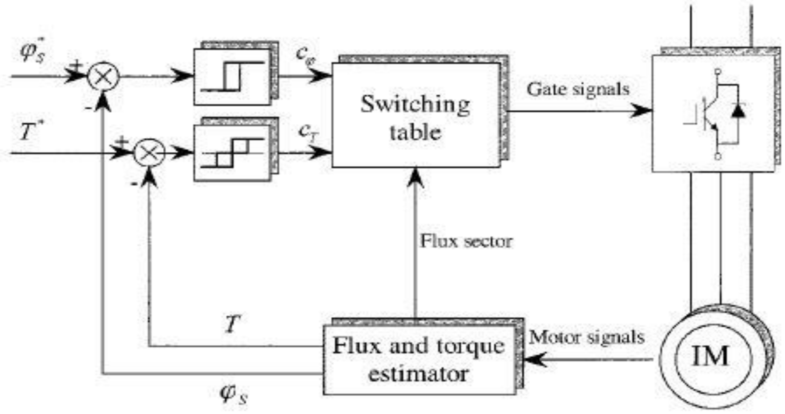



Fig. 2. Basic DTC scheme.

The error between the estimated torque T and the reference torque T* is the input of a three level hysteresis comparator, whereas the error between the estimated stator flux magnitude and the reference stator flux magnitude is the input of a two level hysteresis comparator.

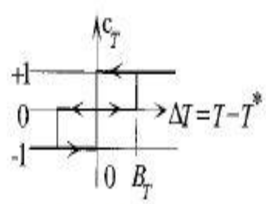


Fig. 3. Torque hysteresis comparator.

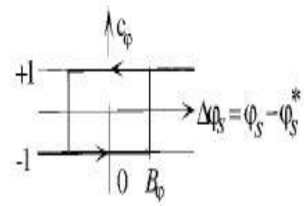


Fig. 4. Flux hysteresis comparator.

The selection of the appropriate voltage vector is based on the switching table given in Table I. The input quantities are the stator flux sector and the outputs of the two hysteresis comparators. Assuming the stator flux vector lying in sector 1 of the dq plane, the voltage vectors used by DTC technique are shown in Fig. 5.

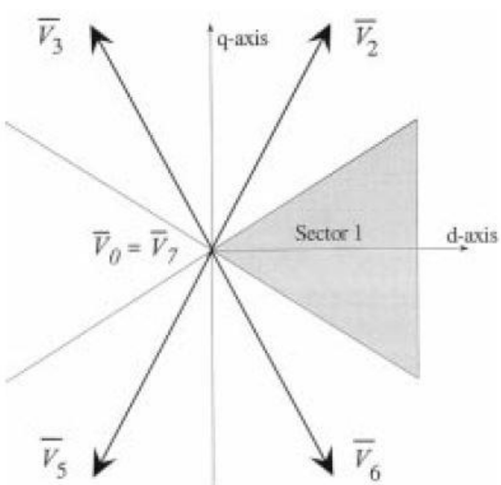



Fig. 5. Voltage vectors utilized in basic DTC scheme when stator flux is in sector 1.

TABLE I
BASIC SWITCHING

| Sector | | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| $c_\varphi = -1$ | $c_T = -1$ | $\overline{V}_2$ | $\overline{V}_3$ | $\overline{V}_4$ | $\overline{V}_5$ | $\overline{V}_6$ | $\overline{V}_1$ |
| | $c_T = 0$ | $\overline{V}_7$ | $\overline{V}_0$ | $\overline{V}_7$ | $\overline{V}_0$ | $\overline{V}_7$ | $\overline{V}_0$ |
| | $c_T = +1$ | $\overline{V}_6$ | $\overline{V}_1$ | $\overline{V}_2$ | $\overline{V}_3$ | $\overline{V}_4$ | $\overline{V}_5$ |
| $c_\varphi = +1$ | $c_T = -1$ | $\overline{V}_3$ | $\overline{V}_4$ | $\overline{V}_5$ | $\overline{V}_6$ | $\overline{V}_1$ | $\overline{V}_2$ |
| | $c_T = 0$ | $\overline{V}_0$ | $\overline{V}_7$ | $\overline{V}_0$ | $\overline{V}_7$ | $\overline{V}_0$ | $\overline{V}_7$ |
| | $c_T = +1$ | $\overline{V}_5$ | $\overline{V}_6$ | $\overline{V}_1$ | $\overline{V}_2$ | $\overline{V}_3$ | $\overline{V}_4$ |

This simple approach allows a quick torque response to be achieved, but the steady-state performance is characterized by undesired ripple in current, flux and torque. This behavior is mainly due to the absence of information about torque and rotor speed values in the voltage vector selection algorithm.

The characteristics of the motor under test are shown in Table II.

TABLE II
MOTOR DATA

| |
|---|
| Standard 3-phase, 4 kW, 4-pole, 220V, 50 Hz induction motor |
| Rated current 16.6 A, Rated torque 26.5 Nm, Rated speed 1440 rpm |

## STEADY-STATE PERFORMANCE

The steady-state performance of DFOC and DTC schemes has been compared evaluating the three-phase rms current ripple in different operating conditions.

TABLE III
THREE-PHASE RMS CURRENT RIPPLE (DFOC)

| Torque \ Speed | 1440 rpm | 720 rpm | 144 rpm |
|---|---|---|---|
| 26.5 Nm | 0.64 A | 0.93 A | 0.58 A |
| 13.25 Nm | 0.64 A | 0.94 A | 0.47 A |
| 0 Nm | 0.65 A | 0.93 A | 0.34 A |

TABLE IV
THREE-PHASE RMS CURRENT RIPPLE (DTC)

| Torque \ Speed | 1440 rpm | 720 rpm | 144 rpm |
|---|---|---|---|
| 26.5 Nm | 1.10 A | 1.57 A | 1.46 A |
| 13.25 Nm | 1.09 A | 1.56 A | 1.27 A |
| 0 Nm | 1.18 A | 1.46 A | 1.21 A |

## TRANSIENT PERFORMANCE

TABLE V
SETTLING TIME OF THE TORQUE RESPONSE

| | FOC | DTC |
|---|---|---|
| 1200 rpm | 3.8 ms | 1.8 ms |
| 600 rpm | 1.8 ms | 0.7 ms |
| 100 rpm | 1.7 ms | 0.5 ms |

## NEW DTC SCHEME (DSVM)

A substantial reduction of current and torque ripple in DTC scheme could be obtained using a preview technique in the calculation of the stator flux vector variation required to exactly compensate the flux and torque errors at each cycle period. In order to apply this principle, the control system should be able to generate any voltage vector (e.g., using the space vector modulation technique). This ideal behavior can be approximated applying, at each cycle period, different voltage vectors for prefixed time intervals, leading to a discrete space vector modulation (DSVM) technique, which requires only a small increase of the computational time. According to this principle of operation, new voltage vectors can be synthesized with respect to those used in basic DTC technique.

It has been verified that subdividing the cycle period in three equal time intervals leads to a substantial reduction of torque and current ripple without the need of too complex switching tables. Using the DSVM technique, with three equal time intervals, 19 voltage vectors can be generated, as represented in Fig. 13.

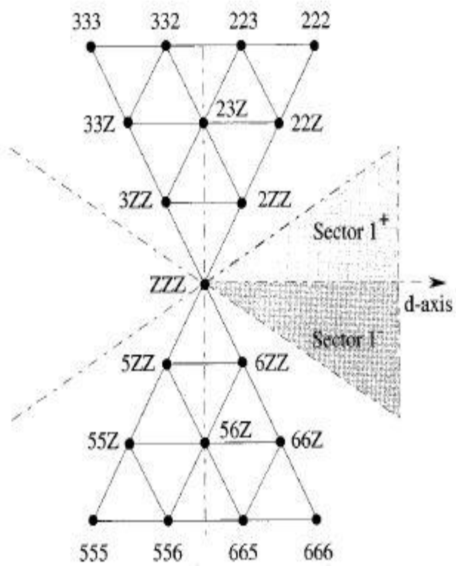



Fig. 13. Voltage vectors generated by using DSVM with three equal time intervals per cycle period.

The black dots represent the ends of the synthesized voltage vectors. As an example, the label "332" denotes the voltage vector which is synthesized by using the voltage space vectors V3 ,V3 and V2, each one applied for one third of the cycle period. The increased number of voltage vectors allows the definition of more accurate switching tables in which the selection of the voltage vectors can be made according to the rotor speed. The switching tables can be derived from the analysis of the equations linking the applied voltage vector to the corresponding torque and flux variations.

In order to show the effectiveness of this new DTC scheme, some numerical simulations have been performed, and the results obtained in terms of current waveform and current spectrum are given in Fig. 16. For comparison purposes, the same quantities are presented for DFOC and DTC in Figs. 14 and 15, respectively. The rotor speed is 144 rpm and the torque 26.5 Nm. The cycle period has been assumed equal to 80 s. The difference with respect to 40 s in DTC is not justified by a so large increase of the computational time, but by the need to keep the mean switching frequency equal to that of DFOC and DTC. It can be noted that the quality of the stator current is similar to that of DFOC scheme. It has been verified that also the torque ripple is similar to that of DFOC scheme.

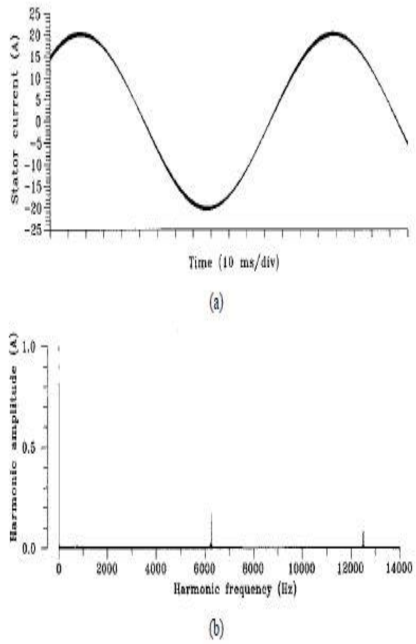



Fig. 14. (a) Stator current (DFOC). (b) Stator current harmonic spectrum (DFOC).

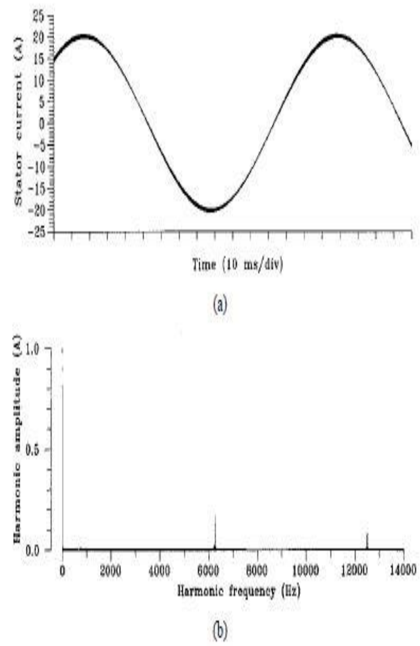



Fig. 14. (a) Stator current (DFOC). (b) Stator current harmonic spectrum (DFOC).

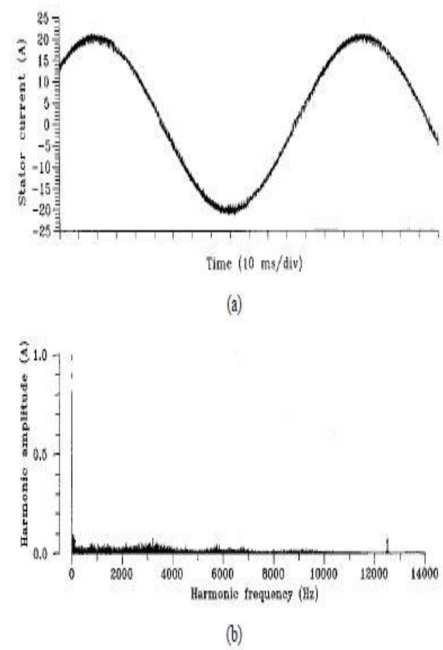



Fig. 16. (a) Stator current (DSVM). (b) Stator current harmonic spectrum (DSVM).

## FIELD WEAKENING

Field weakening is a method of raising the speed in DC motors. If the field (magnetic field) is weakened by reducing field current, back emf is reduced and thereby more armature current is drawn. Now torque is produced due to interaction of armature current and field flux. It is interesting that one quantity (armature current) is increasing while the other (field flux) is decreasing. But the effect of increased armature current on torque happens to be more prominent than the effect of decreased field flux. So the motor accelerates, its speed increases, but at the cost of torque.

So if we want to increase speed without sacrificing torque, field weakening is not recommended. Instead, we should increase speed by increasing armature voltage.

The final goal is to increase the operating speed of the motor without needing to increase the voltage or current required from the power supply. That is to provide increasing speed with constant power. Since mechanical power is speed multiplied by torque, constant power with increasing speed means reducing torque at increasing speed.

Most loads require the same torque or more torque to operate at higher speeds. However, some of the torque used drive a vehicle is used to accelerate inertia and climb hills. Engine driven vehicles have gear boxes that are shifted to progressively higher gear ratios as the speed increases. That is constant power operation. At higher speeds, the rate of acceleration and the ability to climb hills is limited. With electrically driven vehicles, the use of gear shifting can be avoided if the motor can be operated at constant power in the upper part of the speed range. It might be possible to operate over the same speed range without sacrificing high-speed torque, but that would require expensive power capability that only be used a small percentage of the operating time.

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