Adaptive Intelligent Combined Vector Control scheme for Sensorless Induction Drive

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Abstract:- Speed sensorless vector control is the current trend in variable speed industrial AC drives due to its substantial energy efficiency and robustness. The existing Flux Oriented and/or Direct Torque Vector Control of Induction Motor need improvement in dynamic performance interms of ripple free torque and smooth flux operation. In this project a new scheme combining both flux and torque control is developed effectively and its performance during starting, steady state operation and dynamic load changing conditions is analysed by dynamic modeling of a typical three phase three level Voltage source inverter fed induction motor drive with an improved Flux-Torque-speed observer for Feedback in software simulation. The real time implementation of this new technique using DSPIC30F4011 Digital Signal Controller has been proved to be the smart alternative with performance enhancement while maintaining robustness and simplicity.

Key-Words:- Vector Control, Feedback Observer, VSI fed IM, Speed Sensorless drive, Space Vector Modulation (SVM).

1 INTRODUCTION

Modern industries require Variable Speed Drives with the speed maintained accurately independent of load. This saves energy, cost and also improves the system efficiency. Traditionally Induction Motor is employed only as constant speed drive due to inherent simple and rugged construction but complex speed control. But in recent times with the advent of power semiconductor devices and various converter topologies with improved control and estimation methods brought high performance AC drives for industrial applications.

Inverter fed IM control is of scalar or vector control. In the simple V/f scalar control, the voltage and frequency are the control variables. The torque is not under control and no role on space vector position during transient. Contrarily vector control, is valid for dynamic states, i.e., not only magnitude and frequency but also instantaneous positions of voltage, current, and flux space vectors are controlled. The conventional method is FOC, proposed by Hasse [1] and Blaschke [2], even though it gives better performance, the major drawback is it requires coordinate transformation and the control structure dependent on the rotor parameters.

There was a trend toward the standardization of the control systems on the basis of the FOC philosophy, there appeared innovative studies of Depenbrock [3] and of Takahashi and Noguchi [4], which depart from the idea of coordinate transformation and as analogy with DC motor control. It basically had a bang-bang control, which meets very well with on-off operation of the inverter semiconductor power devices and it is commonly referred to as DTC.

Many modifications of the classical ST-DTC scheme aimed at improving starting, very low speed operation, torque ripple reduction, overload conditions, variable switching frequency functioning, and noise level attenuation have been proposed during last decade [6]. Habib proposed a new strategy of deadbeat type Torque and Flux DTC [5]. This is different from the classical DTC in the calculation of the voltage vector to be applied to the machine. Hence a simple Sensorless control of IM has been proposed by Kazmirerkowski [7] implementing simple observer for both Flux and Torque control is required.

In this paper a new scheme is developed which can be seen as simplified S-FOC without current control loops [8] or as classical ST-DTC scheme in which switching table is replaced by modulator and hysteresis torque and flux controllers are replaced by linear PI. Since this combines both the advantages of FOC and DTC this is called as Combined Vector Control. In this scheme Torque and Flux are controlled directly in closed loops, and therefore accurate estimation of motor Flux and Torque is necessary.

Here a high performance Digital Signal Controller has been used which makes the complicated control algorithm a flexible one such that flux vector control can be achieved easily. The novelty of the developed system consists of combining the universal DTC-FSVM structure with a simple observer for both Torque/Flux and Speed Sensorless control.

2 VSI Fed Induction Motor Drive

The block diagram of the complete system is shown in Figure 1. The detail of the components in this experiment is given in Table 1. A three phase Diode Bridge Rectifier changes the incoming alternating current supply to direct current. The DC is then conditioned in the filter circuit. The three phase three level inverter converts the rectified and conditioned DC back to AC of variable frequency and voltage which is given to three phase Induction Motor.

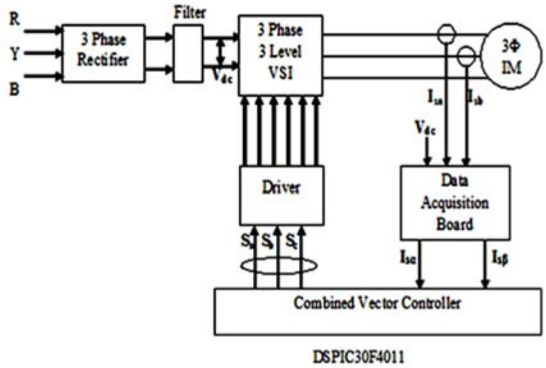


Fig. 1 Three Phase VSI fed Induction Motor Drive

2.1 System modeling

In simulation the three phase squirrel cage Induction Motor is designed using the dynamic $d-q$ model and in particular synchronous reference frame is chosen because it is most convenient frame of reference to study the transient and dynamic characteristics of IM.

The voltages $as - bs - cs$ can be resolved into v_{ds}^s and v_{qs}^s components and can be represented in the matrix form as

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{os}^s \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta-120) & \cos(\theta+120) \\ \sin\theta & \sin(\theta-120) & \sin(\theta+120) \\ 0.5 & 0.5 & 0.5 \end{bmatrix}\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{os} \end{bmatrix} \quad (1)$$

The synchronously rotating d^e-q^e axis rotates at synchronous speed ω_e with respect to the d^s-q^s axes and the angle $\theta_e=\omega_{et}$. The voltages on the d^s-q^s axes can be converted into the d^e-q^e frame as follows:

$$v_{qs} = v_{qs}^s \cos\theta_e - v_{ds}^s \sin\theta_e \quad (2)$$

$$v_{ds} = v_{qs}^s \sin\theta_e + v_{ds}^s \cos\theta_e \quad (3)$$

The torque can be generally expressed in the vector form as

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \quad (4)$$

The Combined Vector Controller unit controls the whole operation of the three phase Induction Motor; it monitors and controls the rectifier, the filter circuit and the inverter to deliver the correct output in response to an external control signal.

2.2 Combined vector control

The Combined Vector Controller block has been shown in Fig 2. A new concept combining the advantages of both conventional FOC and DTC scheme is developed. This scheme shows conventional FOC eliminating the inner current loop and basic DTC eliminating the hysteresis controller and switch table modulator. Thus a PI controller is used for torque regulation. Its output produces an increment in the torque angle, $\Delta\delta_\psi$ [9] [10] as shown in Fig 3. Assuming that the rotor and flux magnitudes are approximately equal, the torque is controlled by changing the torque angle, δ_ψ. The stator flux vector is calculated by addition of the estimated flux position γ_s and change of the torque angle $\Delta\delta_\psi$. Its value is compared with the estimated flux, and the stator flux error $\Delta\psi_s$ produced is directly used for the calculation of VSI switching states in the SVM block [10] [11]. The increment in torque angle corresponds to the increment of stator flux vector. The internal stator flux loop eliminating the flux PI controller is used for the calculation of flux error $\Delta\psi_s$ in flux PWM.

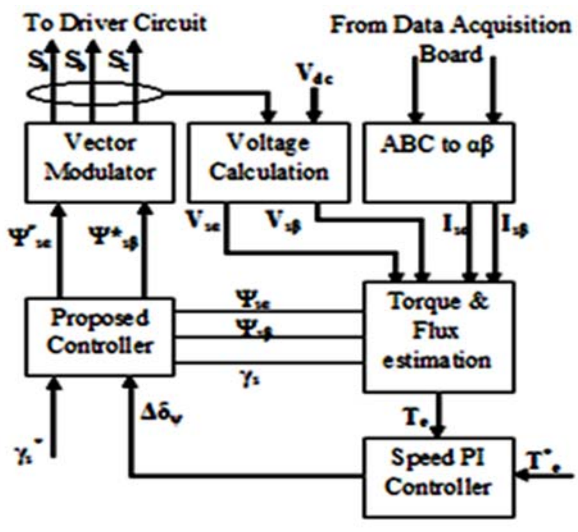


Fig. 2 Proposed Combined Vector Controller

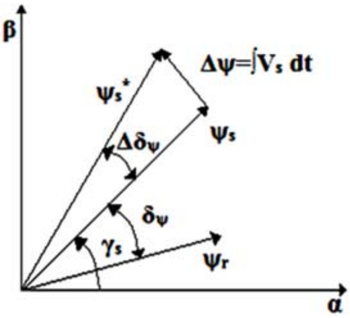


Fig. 3 Vector increment in torque angle

The proposed combined vector control uses a cascaded structure similar to FOC and a vector rotation along with the assumption of known machine torque similar to the DTC. The SVM modulation technique is used to control the inverter output voltage. The eight possible output voltage vectors, six active vectors $V_1 – V_6$ and the two zero vectors V_0, V_7 are shown in Fig 8. The output voltage represented by space vectors is defined as:

$$V_o = \begin{cases} \frac{2}{3} V_c e^{j(v-1)\pi/3}, \ v = 1 \dots\dots 6 \\ 0, \ v = 0{,}7 \end{cases} \quad (8)$$

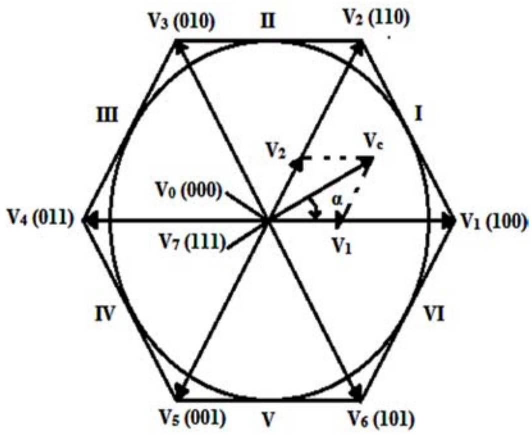


Fig. 4 Principle of Space Vector Modulation

The reference voltage vector V_c is realized by the sequential switching of active and zero vectors. The six active vectors divide a plane for the six sectors I – IV. In the each sector the reference voltage vector V_c is obtained by switching on, for a proper time. The reference voltage vector V_c is sampled with the fixed clock frequency $f_s=1/T$. The residual sampling time T_s is reserved for zero vectors V_0 and V_7.

$$t_{0,7} = T_s - (t_1 + t_2) = t_0 + t_7 \quad (9)$$

The concept of space vector is derived from the rotating field of AC modulating the inverter output voltage. In order to obtain the output of the inverter supported by SVPWM as sinusoidal the reference vector locus with respect to time should be a circle instead of hexagon as locus of the vector sum of three voltages gives a circle. To achieve the above scenario, the vector in each sector is sampled for a specific duration using active and zero vectors and hence we can obtain required vector corresponding instant.

2.3 Torque and flux observer

Implementation of any high performance drive system requires a high accuracy estimation of the actual stator or rotor flux and electromagnetic torque. To avoid the use of the flux sensors or measuring coils the IM *flux estimators* are developed. These are IM equations models with stator voltages and currents.

$$\overrightarrow{\psi_{ds}^{e}} = \int \left(\overrightarrow{V_{ds}^{e}} - R_s \overrightarrow{i_{ds}^{e}}\right) dt \quad (5)$$

$$\overrightarrow{\psi_{qs}^{e}} = \int \left(\overrightarrow{V_{qs}^{e}} - R_s \overrightarrow{i_{qs}^{e}}\right) dt \quad (6)$$

Once the flux vector is accurately estimated, the Torque estimation is performed directly as a cross product of the flux and measured stator current vectors. Thus the electromagnetic torque is obtained as

$$T_e = \frac{3}{2} P \frac{1}{\omega_b} \left(i_{qs}^{e} \psi_{ds}^{e} - i_{ds}^{e} \psi_{qs}^{e}\right) \quad (7)$$

The block diagram of the implemented stator flux vector and Torque estimation according to the equation (5) – (7) is shown in Figure 5.

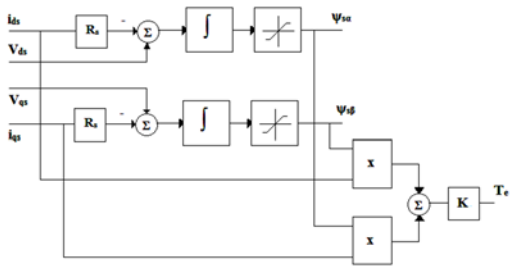


Fig. 5 Block diagram of Torque/flux estimator

2.4 Software Implementation

The Combined Vector Control strategy is implemented in DSPIC30F4011 microcontroller. The programming is done using Embedded C language. A first party complier software MPLAB is used to compile the program. This restricts the user to access the program code from the Microcontroller. The PWM pulses are generated using PWM module in DSPIC30F4011. Some features of PWM module are 6 PWM I/O pins with 3 duty cycle generators, Upto 16-bit resolution, 'On- the- fly' PWM frequency changes. This module contains 3 duty cycle generators, numbered 1 through 3. The module has 6 PWM output pins, numbered PWM1H/PWM1L through PWM3H/PWM3L. The six I/O pins are grouped into high/low numbered pairs, denoted by the suffix H or L, respectively. For complementary loads, the low pins are always the complement of the corresponding high I/O pin. The error signal from the controller is processed to generate the PWM pulses for MOSFET of the three phase three level inverter.

3 Simulation Results and observation

Combined Vector Control method is characterized by much better parameters in steady state operation. In steady state, the current and voltages are taken to be sinusoidal. The simulation result confirms a good dynamics of the flux and proper operation in steady state. The simulation results showing rotor speed, torque and reference torque is shown in Figure 6.

Also the use of linear PI controller operates on values averaged over sampling period. Therefore, the average switching frequency of the inverter in case of conventional control of about 40 kHz can be reduced to 2 – 5 kHz with proposed scheme.

In dynamic analysis of CVC method speed reversal with respect to changes in load torque (T_L) in negative axis, speed tracking performances during starting of motor and step change in speed for changes in load torque are shown in Figure (7 - 9).

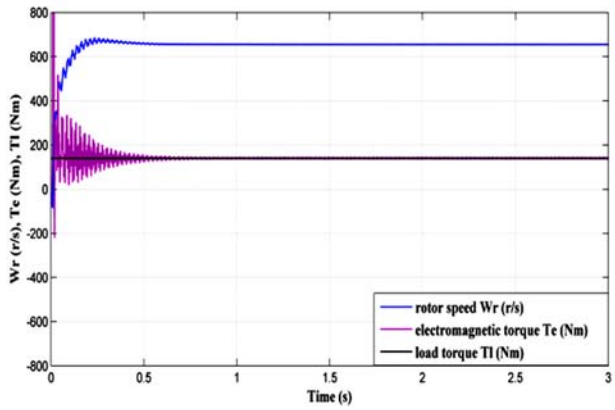


Fig. 6 Simulation waveform for rotor speed, electromagnetic torque, load torque in steady state operation

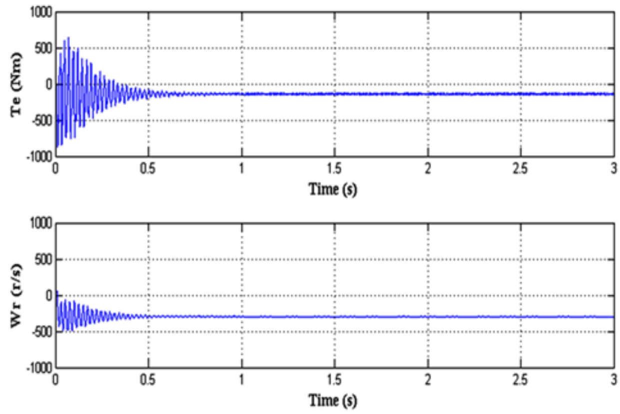


Fig. 7 speed reversal for torque changes

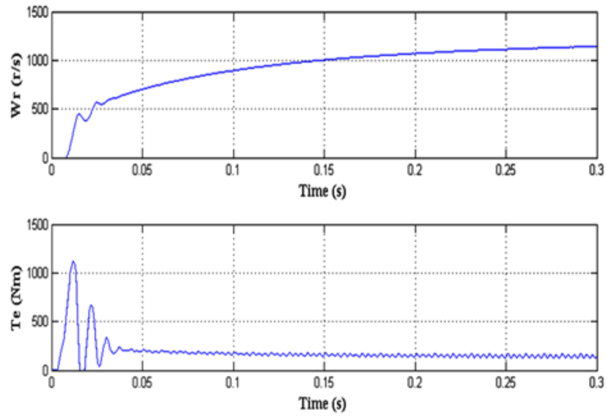


Fig. 8 speed tracking performance of the drive

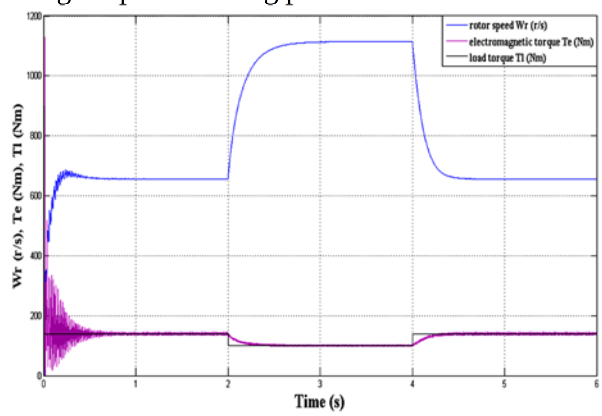


Fig. 9 Change in electromagnetic torque for step changes in load torque

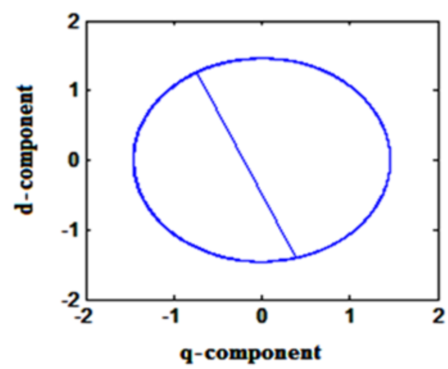


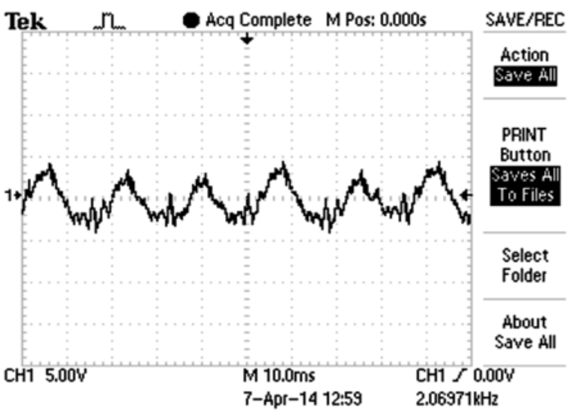
Fig. 10 XY stator flux trajectory

Fig. 10 shows the XY trajectory of the estimated stator flux. The XY trajectory of the estimated stator flux is almost circular showing that the new improved observer used in Combined Vector Control works successfully.

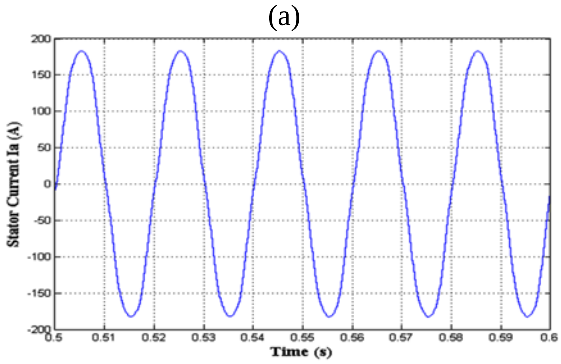
The expected advantages of the CVC will comprise of combined advantages of both FOC and Conventional DTC such as

- Structure independent of rotor parameters.
- Simple implementation of Sensorless operation.
- No coordinate transformation.
- No current control loops.
- Constant switching frequency
- Unipolar inverter output voltage.
- Low sampling frequency.

The experimental model of hardware has been fabricated and tested in laboratory and the observations at different speed conditions were recorded. The MOSFET gate pulses are generated using DSPIC30F4011 microcontroller. Digital storage oscilloscope has been used to measure and display the stator currents of the motor and PWM pulses of the MOSFET switches. The waveforms are measured using a Digital Storage Oscilloscope of 10 MHz frequency with a sampling rate of 1Gsample/ seconds and are taken into display.



(a)

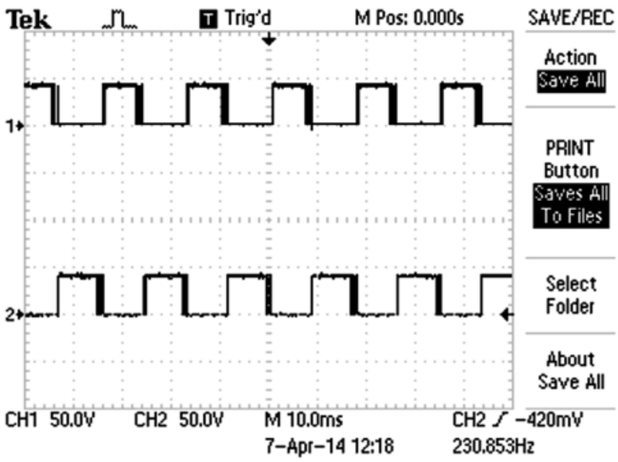


(b)

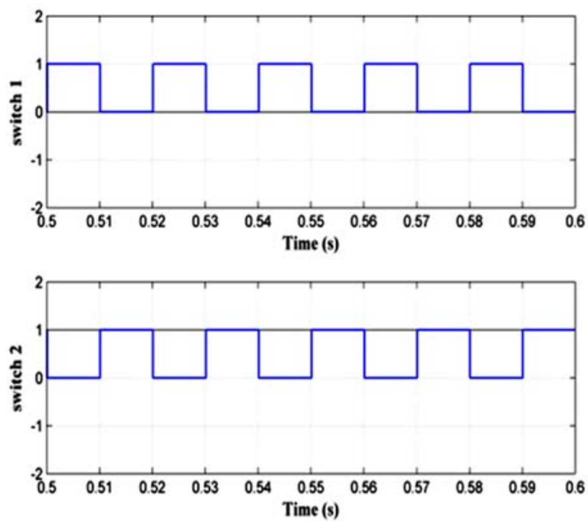
Fig. 11 Comparison between Stator Current waveforms taken in a) Simulation and b) Hardware

The stator current waveforms obtained via the Hall Effect Sensor are found sinusoidal at high rotor speed as shown in Figure 11 (a) is compared with the simulation result shown in Figure 11 (b). At no load, 2 A of stator current flows through the motor.

The PWM pulses generated by SVM algorithm prove a complete control of MOSFET switches. At high speed the pulses given to switch S_1 and S_2 are shown in Figure 12 (a) is compared with the pulses generated during simulation as in Figure 12 (b). The S_1 pulses are given to the upper switch whereas inverted S_2 pulses are given to the lower switch.



(a)



(b)

Fig. 12 Comparison between PWM pulses in a) Simulation b) Hardware

5 Conclusion

In this project a new Combined Vector Control scheme with both Flux Oriented and Direct Torque Control technique is modelled in simulation and hardware. The dynamic mathematical model of IM has been realized successfully. The flux and torque observer with rotor speed estimator for IM drive was developed and modelled effectively. The simulation and experimental results show satisfactory steady state and dynamic performance of the drive even under variable speed and torque condition. A comparative performance analysis of VSI fed IM drive with proposed scheme with the conventional FOC and DTC vector control techniques has been carried out. For the detail simulation results and analysis, it is understood that proposed CVC is a combination of DTC and FOC which eliminates basic disadvantages while keeping main advantages of both methods. Also, operation at constant switching frequency improves considerably the drive performance in terms of reduced torque and flux pulsations reliable start up even under low speed operation.

List of Abbreviations

AC	Alternating Current
CVC	Combined Vector Control
DC	Direct Current
DSC	Digital Signal Controller
DSO	Digital Storage Oscilloscope
DSP	Digital Signal Processor
DTC	Direct Torque Control
DTC-SVM	Direct Torque Control Space Vector Modulation
FOC	Field Oriented Control
IM	Induction Motor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PI	Proportional Integral
PWM	Pulse Width Modulation
SMC	Sliding Mode Controller
ST-DTC	Switch Table Direct Torque Control
SVM	Space Vector Modulation
VSD	Variable Speed Drive
VSI	Voltage Source Inverter

List of Symbols

d^e - q^e	Synchronously Rotating Reference Frame Direct & Quadrature Axis
d^s - q^s	Stationary Reference Frame Direct & Quadrature Axis
i^e_{ds}	Direct Axis Stator Current in synchronous reference frame
i^e_{qs}	Quadrature Axis Stator Current in synchronous reference frame
δ_ψ	Torque Angle
γ	Flux Position Angle
N_s	Synchronous Speed (rpm)
N_r	Rotor Speed (rpm)
P	No of Poles
R_s	Stator Resistance
T_e	Electromagnetic Torque
T_L	Electromagnetic Torque
V^e_{ds}	d^s- Axis Stator Voltage in synchronous reference frame
V^e_{qs}	q^e -Axis Stator Voltage in synchronous reference frame
ψ_r	Rotor Flux Linkage
ψ_s	Stator Flux Linkage
$\psi_{ds}{}^e$	d^s- AXIS STATOR FLUX LINKAGE in synchronous reference frame
$\psi_{qs}{}^e$	q^e - AXIS STATOR FLUX LINKAGE in synchronous reference frame
ω_e	Supply Frequency(r/s)

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