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Direct Torque Control of Permanent Magnet Synchronous Motor with Reduced Torque Using Sinusoidal Pulse Width Modulation

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Abstract

Permanent Magnet Synchronous Motor (PMSM) has been widely used in the low and medium power system due to its characteristics of high efficiency, high reliability, and high torque to inertia ratio, smooth torque and fast dynamic response. In conventional direct torque controlled (DTC) Permanent Magnet Synchronous Motor (PMSM) drive, there is usually undesired torque and flux ripple. This report proposes the simulation implementation of PMSM drive using Sinusoidal Pulse Width Modulation (SPWM) which is easier to implement. The simulation result shows that by using SPWM technique, the torque ripples reduced is very less with easier implementation. The design, analysis and simulation of SPWM based DTC of PMSM is simulated using MATLAB SIMULINK Version 7.2 and the simulation results are discussed.

Index terms—Direct Torque Control (DTC), Sinusoidal Pulse Width Modulation (SPWM), and Permanent Magnet Synchronous Motor (PMSM). **Reviewed by* **ICETSET'16** *organizing committee*

I. INTRODUCTION

PMSM has been widely used in the low and medium power system due to its characteristics of high efficiency, high reliability, high torque to inertia ratio, smooth torque and fast dynamic response. In general, a sensor like optical encoder is necessary for the PMSM control system in order to obtain the rotor position and speed. Normally the controlling of the torque of PMSM usually follows either the most popular Direct Torque Control (DTC) or Field Oriented Control (FOC). In this paper the direct torque control method is used to control the torque. In this method the pulse production to the inverter is been generated by using Sinusoidal Pulse Width Modulation (SPWM).

The switching of the power inverter constitutes the harmonics in PMSM and leads to variable switching frequency and high current ripples. The harmonics generated by power inverter which will leads to high torque pulsation and load disturbance. In last decades, many schemes have been proposed to address these problems of conventional DTC. Many of the methods employ space vector modulation (SVM) to produce continuous voltage vectors, which in turn adjusts the torque and flux more accurately and hence the torque and flux ripples were reduced with fixed switching frequency.

Another advantage of using SVM is that the sampling frequency does not need to be as high as that in conventional DTC. Alternative method of modified DTC does not require the SVM block and calculations were implemented in stationary coordinate, hence preserving the advantages of conventional DTC. Multilevel inverters were introduced to obtain more voltage vectors [9], [10]; however, the cost of hardware and system complexity is increased.

The DTC requires the information of stator flux and by integrating the back electromotive force behind the stator resistance this can be calculated from the voltage mode. However, in practical, pure integration usually suffers from the dc drift and initial value [11]–[15]. To overcome these problems, low-pass filter (LPF) was proposed to replace pure integration [11]. This causes errors in magnitude and as well as in phase when the cutoff frequency is greater than the motor frequency, so compensation is necessary. The compensation method in [12] requires twice transformation and/or Incorporation of PI, which increases the system complexity and the other method, employs cascaded programmable LPF [13] to improve the accuracy of LPF; however, its dynamic performance is poor [14] and the computation complexity is increased.

II. MODELLING OF PMSM

A. Machine Equations

For PMSM, the model in rotor synchronous coordinate is the most popular, because all the parameters become constant. The machine equations of a PMSM in synchronous frame are expressed as follows (the components indicated by *dq*) $ud = Rs\ id + d\psi d/d$ (2.1)

$uq = Rs\ iq + d\psi q/dt + \omega\psi d$ (2.2)

$\psi d = Ld\ id + \psi f$ (2.3)

$\psi q = Lq\ iq$ (2.4)

where, *Rs* - stator resistance

Ld, *L q*- *d*-axis and *q*-axis inductance

Ψf- permanent magnet flux

ψd, ψq- *d*-axis and *q*-axis stator flux

ud, uq- *d*-axis and *q*-axis stator voltage

id, iq- *d*-axis and *q*-axis stator current

ω- electrical rotor speed

and the torque is expressed as

$Te = (3/2)p\ (\psi d\ iq - \psi q\ id)$ (2.5)

$\psi\alpha = L\alpha\ i\alpha + L\alpha\beta\ i\beta + \psi f \cos\theta e$ (2.8)

$\psi\beta = L\alpha\beta\ i\alpha + L\beta\ i\beta + \psi f \sin\theta e$

II. EXISTING SYSTEM

Direct Torque Control principle for PMSM:

The basic principle of vector control is to get a high-performance system through controlling flux and torque independently after getting the motor decoupling model through coordinate transformation. There are 3 signals which affect the control action in a DTC system;

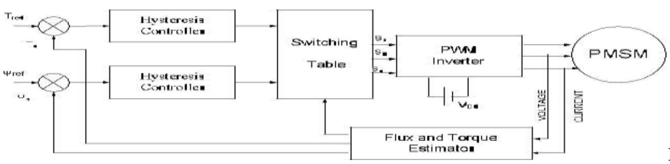
1. Torque - Te
2. The amplitude of the Stator Flux linkage - |ψ |

3. The angle of the resultant flux linkage vectors - δ

A. The Implementation of DTC System

The existing DTC scheme is indicated in figure 1, torque and flux signals are obtained from the estimator. These are regulated by using two hysteresis controllers. The hysteresis controllers outputs in turn switch the three inverter legs,

applying a set of voltage vectors across the motor



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B.Flux and Torque Estimator

Flux and torque estimator are used to determine the actual value of the torque and flux linkage. Into this block enters the VSI voltage vector transformed to the qd-stationary reference frame. The three-phase variables are transformed into dq axes variables with the following transformationwhere *f* represents the stator currents, voltages and flux linkages.

The stator flux linkage is estimated by taking the integral of difference between the input voltage and the voltage drop across the stator resistance as,

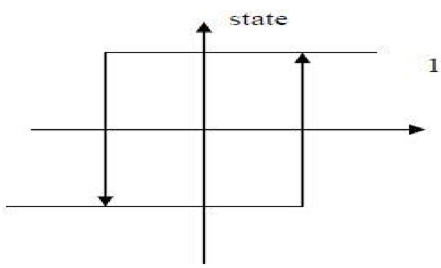
$$\psi_q = \int (V_q - R_s i_q)\, dt \quad (3.1)$$

$$\psi_d = \int (V_d - R_s i_d)\, dt \quad (3.2)$$

The flux linkage phasor is given by

$$\psi_s = \sqrt{(\psi_d^2 + \psi_q^2)} \quad (3.3)$$

In this block, the location of stator flux linkage (θ) is



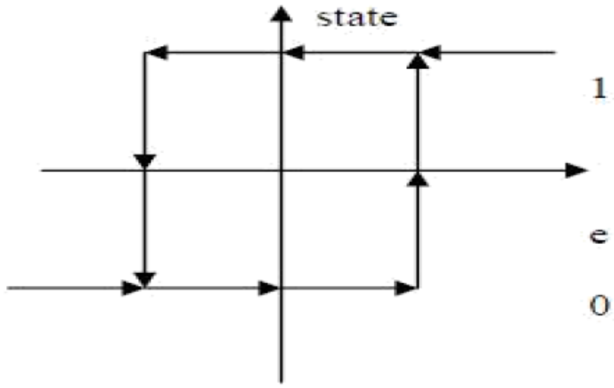


Fig. 3 2-level flux hysteresis comparator

Fig. 2 2-level torque hysteresis comparator

3.3.1 PRINCIPLE OF SPACE VECTOR

The space vector pulse width modulation is used to generate the voltages applied to the stator phases. It uses a special scheme to switch the power transistors to generate pseudo sinusoidal currents in the stator phases. This method is increasingly used for AC drives with the condition that the harmonic current is as small as possible and the maximum output voltage is as large as possible.

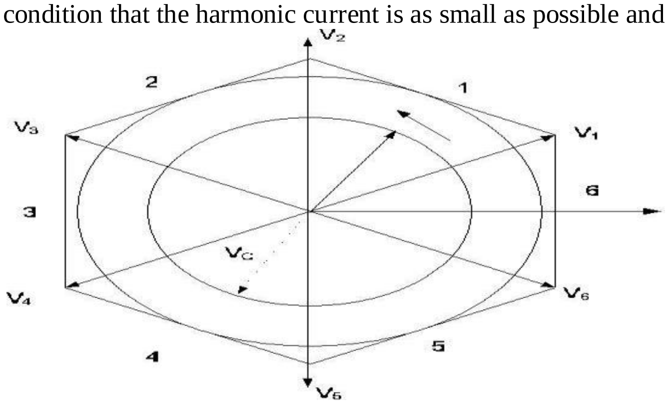


Fig. 4 Switching vectors and sector

Treats the sinusoidal voltage as a constant amplitude vector rotating at constant frequency. This PWM technique approximates the reference voltage Vref by a combination of the eight switching patterns (V0 to V7). Coordinate Transformation (abc reference frame to the stationary α-β frame). That is a three-phase voltage vector is transformed into a vector in the stationary α-β coordinate frame represents the spatial vector sum of the three- phase voltage. The vectors (V1 to V6) divide the plane into six sectors (each sector: 60 degrees).Vref is generated by two adjacent non-zero vectors and two zero vectors. To implement the space vector PWM, the voltage equations in the abc reference frame can be transformed into the stationary αβ reference frame that consists of the horizontal (α) and vertical (β) axes, as a result, six non-zero vectors and two zero vectors are possible. Six nonzero vectors (V1 - V6) shape the axes of a hexagonal as depicted in figure 3.6 and feed electric power to the load or DC link voltage is supplied to the load. The angle between any adjacent two non-zero vectors is 60 degrees. Meanwhile, two zero vectors (V0 and V7) are at the origin and apply zero voltage to the load. The eight vectors are called the basic space vectors and are denoted by V0, V1, V2, V3, V4, V5, V6, and V7.

The same transformation can be applied to the desired output voltage to get the desired reference voltage vector Vref in the d-q plane. The objective of space vector PWM technique is to approximate the reference voltage vector Vref using the eight switching patterns.

The space vector pulse width modulation is used to generate the voltages applied to the stator phases. It uses a special scheme to switch the power transistors to generate pseudo sinusoidal currents in the stator phases. The space vectors technique is nowadays commonly known as space vector modulation (SVM).

The SVPWM switching pattern is shown in the fig. 5, it consists of eight vectors starting from V_0 to V_7.

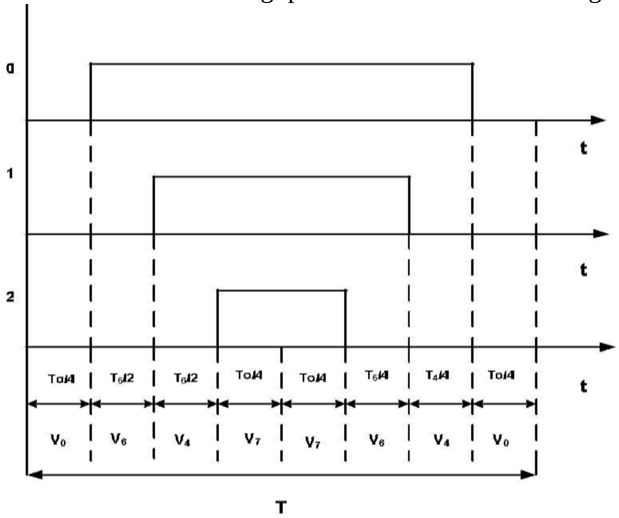


Fig.5 SVPWM switching pattern

IV. PROPOSED SYSTEM WITH SINUSOIDAL PULSE WIDTH MODULATION

Pulse width modulation is the process of modifying the width of the pulses in a pulse train in direct proportion to a small control signal. There are different types of pulse width modulations. Among them, the well known are Sinusoidal pulse width modulation (SPWM). Sinusoidal PWM has been very popular technique used in AC motor control. This method employs a triangular carrier wave compared with a sine wave and the points of intersection determine the switching points of the power devices in the inverter. However, this method is unable to make full use of the inverter's supply voltage and the asymmetrical nature of the PWM switching characteristics produces relatively high harmonic distortion when compared to SVPWM.

A. Generation of Gating Signals

Instead of maintaining the width of all pulses as same, the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the center of the same pulse. The SPWM is commonly used in industrial applications. The frequency of the reference signal f_r determines the inverter output frequency f_o, and the reference peak amplitude controls the Modulation Index (MI), and in turn the rms output voltage.

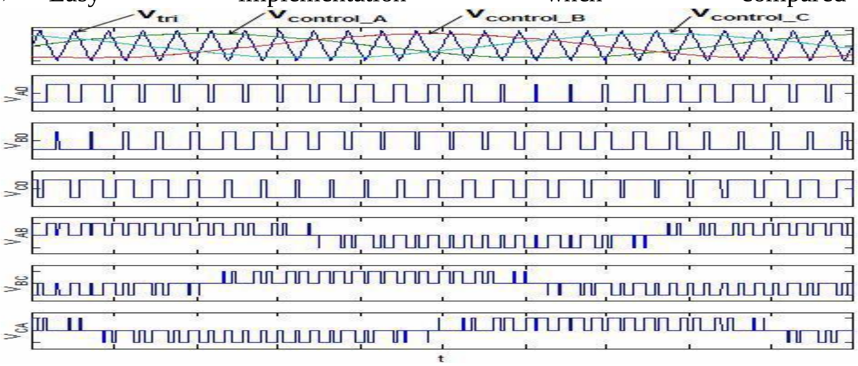
The generations of gating signals with SPWM are shown in fig. 6. There are three sinusoidal reference waves and each shifted by 120º. A carrier wave is compared with the reference signal corresponding to a phase to generate the gating signals for that phase. Comparing the carrier signal with the reference phases it produces the gating pulses. When the sinusoidal wave has magnitude higher than the triangular wave, the comparator output is high, otherwise low. The number of pulses per half cycles depends upon the carrier frequency. When the triangular wave has its peak coincident with zero of the reference sinusoidal, there are $N=f_c/2f$ pulses per half cycle. If zero of the triangular wave coincides with zero of the reference sinusoidal, there are (N-1) pulses per half cycle.

The normalized carrier frequency should be odd multiple of three. Thus, all phase voltage are identical, but 120º out of phase without even harmonics; moreover, at frequencies multiples of three are identical in amplitude and phase in all phases. The rms output voltage can be varied by varying the Modulation Index (MI). It can be observed that the area of each pulse corresponds approximately to the area under the sine wave between the adjacent midpoints of off periods on the gating signals.

B. Advantages

- The Distortion Factor (DF) is reduced.
- The Lowest Order Harmonic (LOH) content is also reduced significantly.

- Easy implementation when compared to SVPWM.



As shown in fig. 6, the frequency of Vtri and Vcontrol is:

- Frequency of Vtri = fs

- Frequency of Vcontrol = f1

where, fs = PWM frequency and f1 = Fundamental frequency The inverter output voltages are determined as follows:

- When Vcontrol > Vtri, VA0 = Vdc/2

- When Vcontrol < Vtri, VA0 = −Vdc/2 where,

VAB = VA0 – VB0, VBC = VB0 – VC0, VCA = VC0 – VA0

C. Modulation Index

The ratio of sinusoidal reference wave to triangular carrier wave is called modulation index. The magnitude of fundamental component of output voltage is proportional to MI. MI can never be more that unity and hence by varying MI, we can control the output voltage.

The frequency modulation ratio is given by,

$$m_f = \frac{f_s}{f_1}$$

- Frequency modulation ratio (m_f) should be a multiple of 3 for three-phase PWM inverter, an odd multiple of 3 and even harmonics are suppressed.

D. Overmodulation:

Further increase in the amplitude of load voltage, the amplitude of the modulating signal can be made higher than the amplitude of the carrier signal which leads to overmodulation. The relationship between the amplitude of the fundamental ac output line voltage and the dc link voltage becomes nonlinear. Large values of MI in SPWM leads to full overmodulation. This case is known as square-wave operation, where the power devices are ON for 180º. Here the inverter cannot vary the load voltage except by varying the dc supply voltage.

V. RESULT AND DISCUSSION

The simulation results for DTC based PMSM drive using SPWM technique are discussed. The system built in

simulink for a PMSM drive system has been tested at the constant power-region of operation.
The motor was controlled by SPWM technique and the waveform of electromagnetic torque output and dynamic torque output is shown if fig. 7, 8.

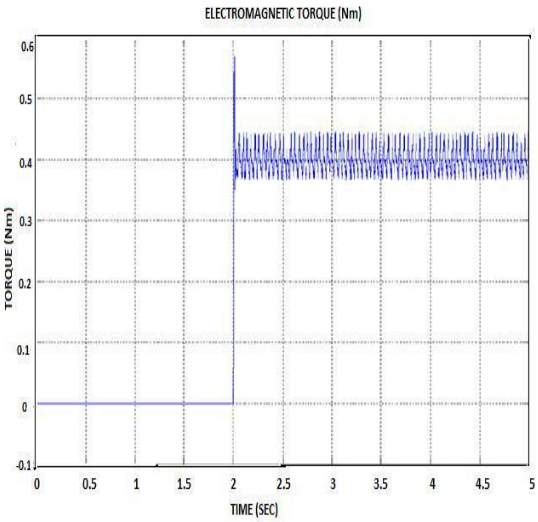


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Fig 7 Electromagnetic Torque Output (Torque=0.4Nm)

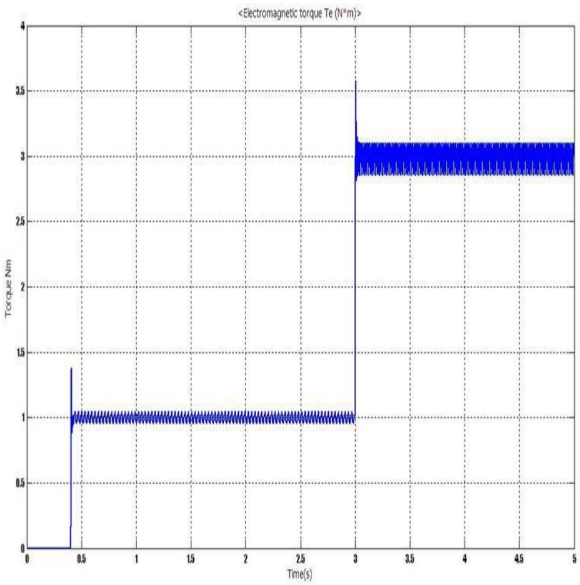


Fig. 8

Dynamic Torque output

The stator currents and dynamic static current output waveforms are shown in fig. 9, 10.

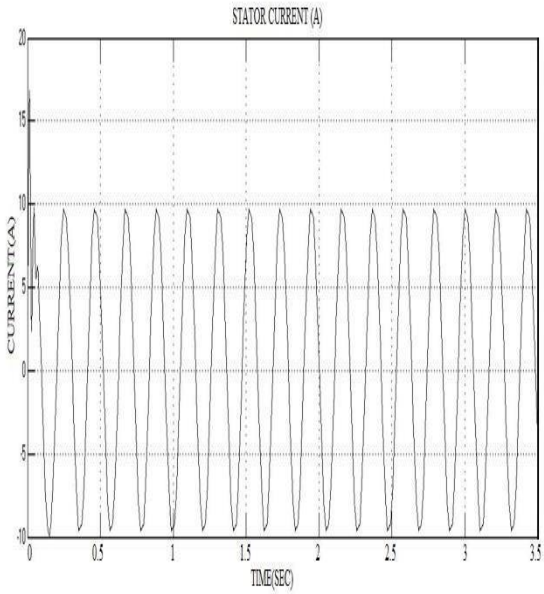
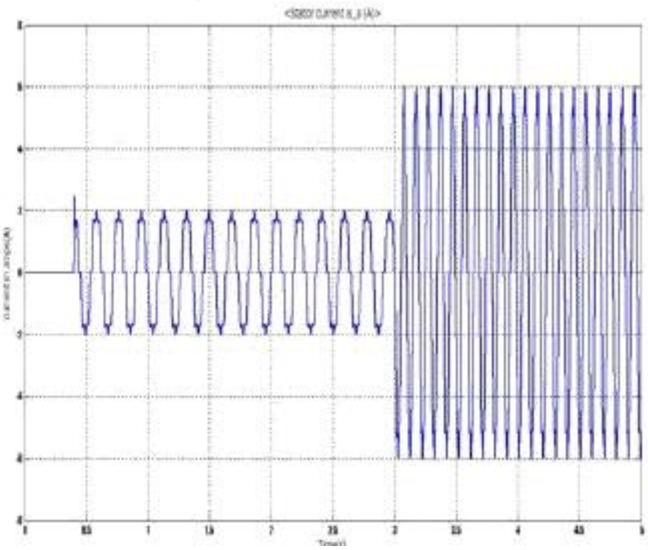


Fig. 9 Stator Current Output



` Fig. 11 Dynamic Static Current

Torque pulsations are less in case of the proposed system. It is clear that a SPWM techinque based torque controller achieves the minimum torque ripple. Also, SPWM based DTC as better current and torque characteristics.

The percentage of ripples obtained by using SPWM the ripple is 4.2%. This percentage ripple obtained by using SPWM is similar to SVPWM technique. Thus by using simple implementation like SPWM, the torque ripple is reduced similar to that of using complicated technique SVPWM. Also the current waveform is similar as in the case of SVPWM.

VI. CONCLUSION

This paper explains the mathematical equations related to the application of DTC in PMSM. The equations show that the change of torque can be controlled by keeping the amplitude of the stator flux linkage constant and increasing the rotating speed of the stator flux linkage as fast as possible. The simulink block of DTC in PMSM using SPWM is presented. The simulation results examined the implementation of the direct torque control in permanent magnet synchronous motor using SPWM and compared its performance with using SVPWM. The torque and flux linkage reference are kept constant at the same level.

VII. APPENDIX

MOTOR PARAMETERS

Type	PMSM
Rated Power	1HP
Number of phases	3
Number of poles (P)	8
Base current	2.5 A
Rated voltage	300 V
Stator resistance per phase(R)	0.9585 ohm
q-axis inductance(Lq)	0.002075 H
Stator flux linkages per p due to rotor magnet (A f) (rad/s)	0.002075H
Moment of inertia (J)	
Friction Factor (F)	
0.0003035(N.m.s)	
d-axis inductance (Ld)	

VII. REFERENCES

[1] Helsinki. Tech.Guide, 'Direct torque control-the world moat advanced Ac drive technology',ABB Finland

[2] BIMBAL.K.Bose (2002) 'Modern power electronics and AC drives' Englewood Chiffs, Prentice-Hall.

[3] Krishnan R. (2002) 'Electric motor drives modelling, analysis, and control', Eastern Economy Edition

[4] V. Ambrozic, G. S, Buja and R. Menis, "Band constrained technique for direct torque control of induction motor," IEEE Trans. Ind. Electron., vol. no. 4, pp. 776-784, Aug. 2004

[5] G. S. Buja and M. P. Kazmierkowski, "Direct torque control of PWM inverter- fed AC motors- A survey,"

IEEE Trans, Power Electron., vol.51, no.4,pp, 744-757, Aug. 2004

[6] Bimal K. Bose, "A High-Performance Inverter-Fed

Drive System of an Interior Permanent Magnet Synchronous Machine," *IEEE Transactions on Industry Application*, vol 24, no.6.

[7] Pragasen Pillay, "Modelling, Simulation and Analysis of Permanent Magnet Motor Drives,*" IEEE Transaction On Industry Application*, vol 25.

[8] V. Ambrozic, G. S, Buja and R. Menis, "Band constrained technique for direct torque control of induction motor," *IEEE Trans. Ind. Electron.*, vol. no. 4, pp. 776-784, Aug. 2004.

[9] S. Kouro, R. Bernal, H. Miranda, C. Silva, and J. Rodriguez, "Highperformance torque and flux control for multilevel inverter fed induction motors," *IEEE Trans. Power Electron.*, vol. 22, no. 6, pp. 2116–2123, Nov. 2007.

[10] Y. Zhang, J. Zhu,Y. Guo,W. Xu,Y.Wang, and Z. Zhao,

“A sensorlessDTC strategy of induction motor fed by three-level inverter based on discrete space vector modulation,” in *Proc. Australasian Univ. Power Eng. Conf. (AUPEC 2009)*, pp. 1–6..
[11] K. D. Hurst, T. G. Habetler, G. Griva, and F. Profumo, “Zero-speed tacholess IM torque control: Simply a matter of stator voltage integration,” *IEEE Trans. Ind. Appl.*, vol. 34, no. 4, pp. 790–795, Jul. 1998.

[12] J. Hu and B. Wu, “New integration algorithms for estimating motor flux over a wide speed range,” *IEEE Trans. Power Electron.*, vol. 13, no. 5, pp. 969–977, Sep. 1998.

[13] B. K. Bose and N. R. Patel, “A programmable cascaded low-pass filter based flux synthesis for a stator flux-oriented vector-controlled induction motor drive,” *IEEE Trans. Ind. Electron.*, vol. 44, no. 1, pp. 140–143, Feb. 1997.

[14] T.-W. Chun, M.-K. Choi, and B. K. Bose, “A novel startup scheme of stator-flux-oriented vector-controlled