Analysis and Control of BLDC Motor

DISSERTATION/THESIS

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I, **Tanya Agarwal**, Roll No. 2K20/PES/22 student of M.Tech (Power Electronics & System), hereby declare that the project Dissertation titled **"Analysis and Control of BLDC Motor"** which is submitted by me to the Department of Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously submitted for the award of any Degree, Diploma.

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I, **Tanya Agarwal**, Roll No. 2K20/PES/22 student of M. Tech. (Power Electronics & System), hereby declare that the dissertation/project titled **"Analysis and Control of BLDC Motor"** under the supervision of Dr. Prakash Chittora, has not been submitted elsewhere for the award of any Degree.

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ABSTRACT

In the present situation, as demand of electricity is increasing, it is essential to think about reduction in the electricity demand and it may be reduced by using a (permanent magnet) BLDC motor as it consumes very less power as compare to Induction motor.

The BLDC motor is broadly used in applications where low and medium power. The BLDC motor is broadly used in automotive, automated industrial equipment, aerospace, medical, consumer, and instrumentation. The main advantage of this over a period of time is the long-term use of this motor.

In BLDC motor, commutation is done electrically by means of switches instead of commutator and brushes which are used in DC motor. Comparing with an induction motor or DC motor, the BLDC motor has following advantages:

1. Lighter in weight
2. More efficient
3. Better controllability
4. Higher speed range
5. Stable performance even with unstable voltage conditions
6. Good dynamic response
7. Lower acoustic noise
8. Better speed versus torque characteristics
9. Longer life

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LIST OF SYMBOLS

AC	Alternating Current
Back- EMF	Back Electromagnetic Force
BLDC	Brushless DC Motor
DC	Direct Current
FOC	Field Oriented Control
I/O	Input/ Output
PFC	Power Factor Correction
PI Controller	Proportional Integral Controller
PWM	Pulse Width Modulation
RPM	Revolutions Per Minute
SVM	Space Vector Modulation

CHAPTER1

INTRODUCTION OF BLDCM (Brushless DC Motor)

1.1 Stator of BLDC Motor

There are three types of the BLDC motor [1] based on phase. Fig1.1 shows the stator diagram for single and three phase.

a) single-phase,

b) two-phase and

c) three-phase.

The single-phase and three-phase motors are the most commonly used.

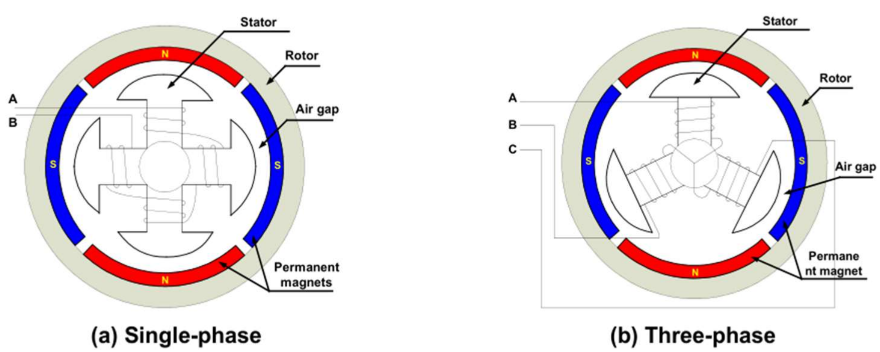

Fig.1.1: BLDC Stator Diagrams

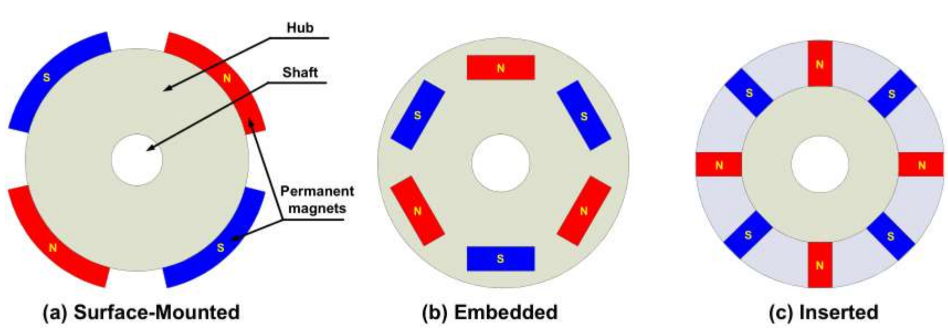

Fig.1.2: Rotor Magnets Cross-Sections

1.2 Rotor of BLDC Motor- A rotor [1] contains a shaft with a hub and permanent magnets are organized to form 2 to 8 pole pairs. These changes from north to south poles. There are many magnet materials, such as rare-earth alloys and ferrous mixtures. Rotor Magnet cross- section can be seen in fig.1.2.

1.3 Types of stator windings-

BLDCM can have 2 forms of stator windings [2] as seen in fig 1.3-

a) Trapezoidal and
b) Sinusoidal

The different types of winding discuss the shape of the BEMF waveform. According to the BEMF produced in the motor, the phase current also tracks a trapezoidal or sinusoidal shape. The shape of the Back-EMF is regulated by different coil interconnections and the distance of the air gap.

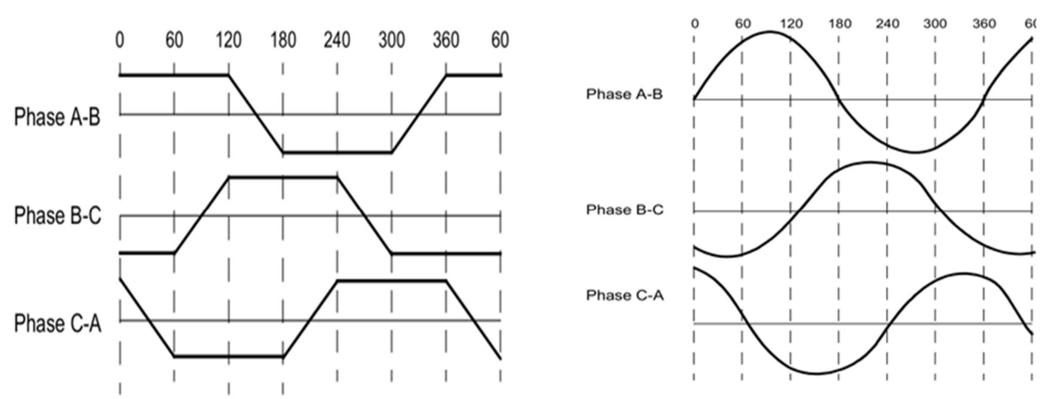

Fig 1.3: Trapezoidal and Sinusoidal stator windings

1.4 Working of 3-phase BLDC Motor

3-phase BLDC motor uses 3- Hall sensors so that the position of the rotor can be detected. These 3- Hall sensors— named as A, B, and C are placed on the stator of the motor at 120° angle intervals, while the 3-phase windings which are connected in either a star or delta. In every 60° of turn of rotor, one of the Hall sensors converts its code (state). So, in all 6-steps, a complete electrical cycle gets over as shown in Fig.1.4. The phase current sequence changes after every 60° [1]. For each state, the one of the motor terminal goes high and the other one terminal of the motor goes low, and the third one terminal left floating. Each and every step regulates the high drive (state 1 of BEMF), low drive (state -1 of BEMF), and floating drive at each motor terminal.

1.5 Sensored and Sensorless BLDC Motor-

BLDC sensor less driver circuit (inverter) checks the BEMF signals in place of the position of the rotor detected by Hall sensors to generate the signal. Sensor less technique also simplifies the motor construction and decrease the motor cost. These BEMF signals are proportional to the speed of rotor's rotation [1]. sensors in these motors cannot be operated where the rotor of the motor is in a closed housing and requires minimal electrical entries, for example, a compressor or the places where the motor is immersed

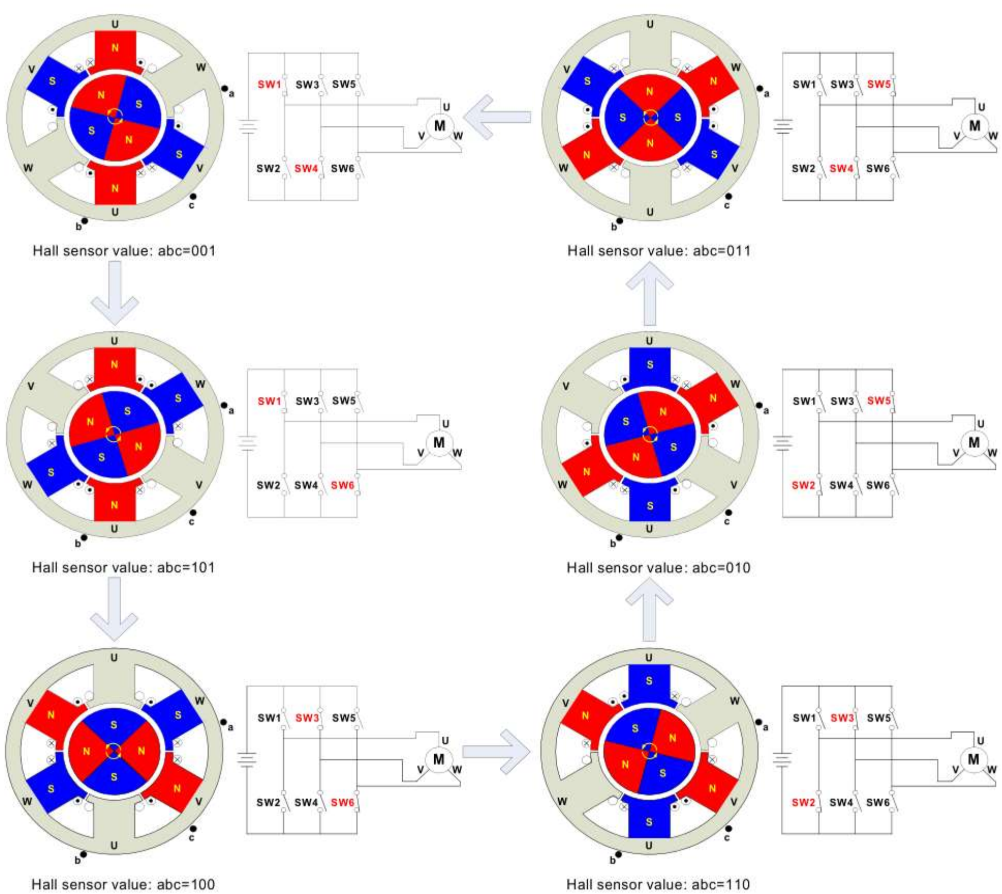

Fig.1.4: Three-Phase BLDC Motor working

in a liquid. Fig 1.5. shows the Hall Sensor versus BEMF of BLDC Motor. Sensored requires additional components but control is easier And Sensorless requires fewer components but control is harder.

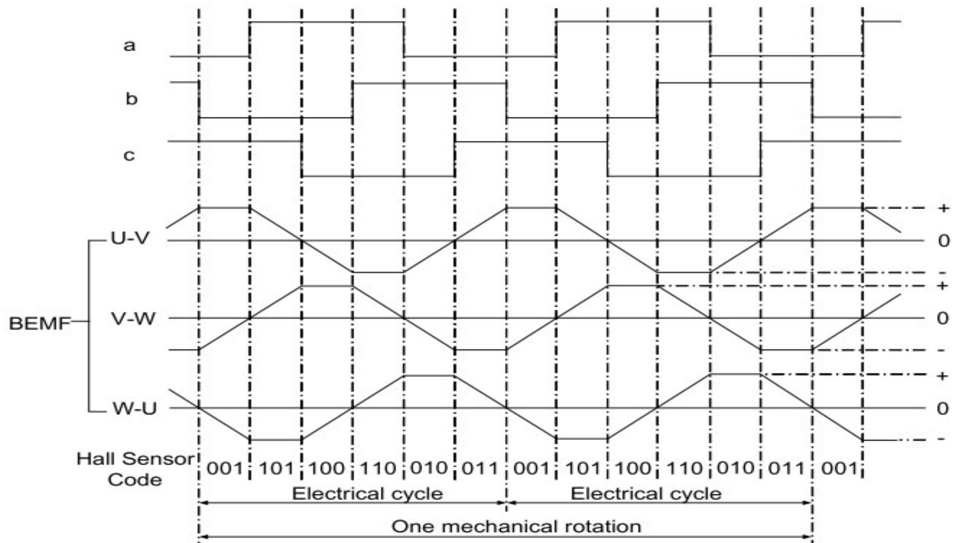

Fig.1.5: Hall Sensor versus BEMF

1.6 How to detect position by BEMF signals? -

There are 2 methods to detect the BEMF Signals.

1. By Measurement
2. By Estimation or Calculation

As the moto is spinning, it is generating this back EMF. Each phase is generating a back EMF signal. By measuring this back EMF at the zero crossing, a code similar to hall sensor can be generated. For detecting this, a comparator is used. The comparator will flip from 0 to 1 or 1 to 0, and this works as a commutation signal, just like a Hall sensor. So, this how we can measure the BEMF signals.

While Using Sinusoidal Method or FOC, this method of measuring the BEMF signals does not work because all three phases are being driven simultaneously. So, we can estimate or calculate back EMF by using equation [3]. Fig. 1.6 shows the rotor detection methods.

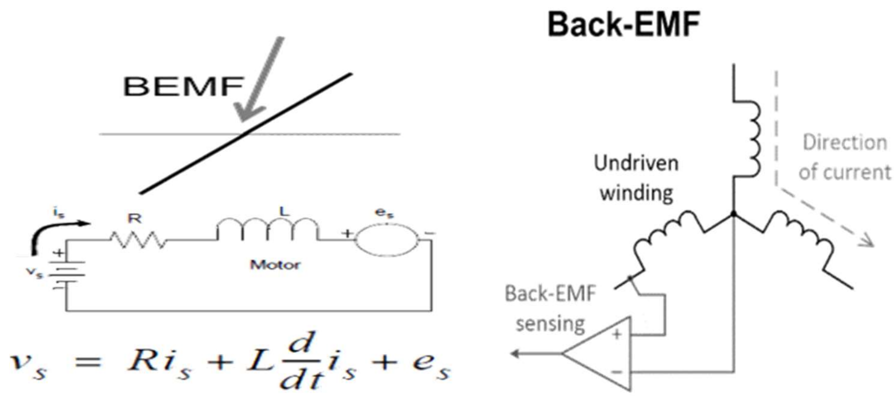

Fig.1.6: BEMF Detection Method

1.7 Driving Methods-

There are 3 methods to drive BLDC motor

a) Square-wave control
b) Sine wave control
c) FOC Control

1.7.1 **Square-wave control-** This method [3] is also called Trapezoidal wave control and 120-degree commutation control as in Fig 1.7. It can actually spin the motor as fast as possibly can. It is the easiest way to get a motor spinning very fast. It is very

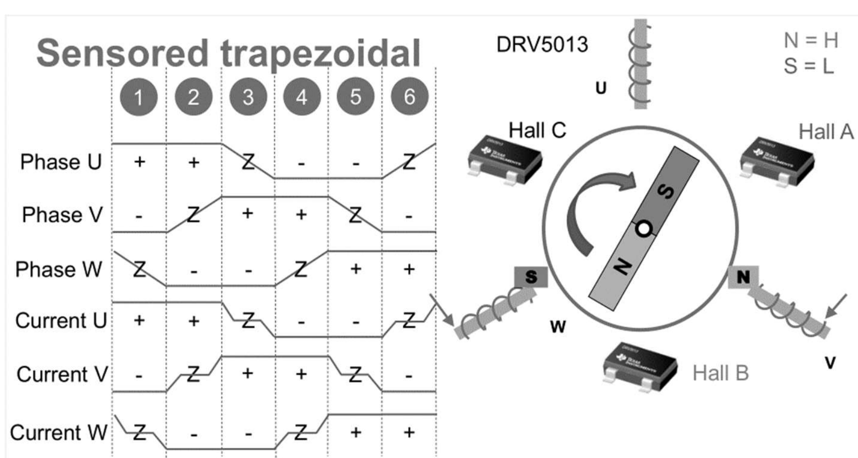

Fig.1.7: Sensored Trapezoidal Control

good at delivering maximum torque into a motor. There is the most power applied to the motor. It has the lowest switching loss. A trapezoidal implementation is the easiest to get a motor to spin. But the drawbacks are- It is not the best in terms of noise, efficiency is not the best and gives noisy performance.

1.7.2 **Sin-wave control-** This method [3] is also called SPWM / SPVWM Control and 180-degree commutation Control as shown by Fig 1.8. As in trapezoidal, there is either on/off, 100% reverse, 100% in the forward direction of current. Now, with electrical commutation, smoother voltage waveforms or current waveforms is applied by PWM switching in this control. sine wave control has smaller torque ripple as compare to other methods and also less current harmonics than the trapezoidal control. Advantage of sine is it is really low noise and it can spin the motor very, very quietly. The disadvantages of sine, PWM have to be given for every single phase all the time. So, switching losses are s three times higher than a trapezoidal system. So due to lot of

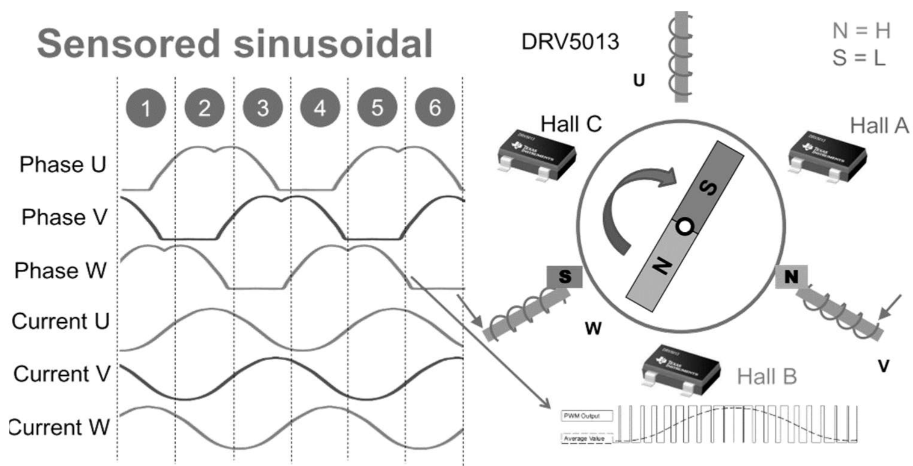

Fig.1.8: Sensored Sinusoidal Control

switching losses, system can get hotter.

1.7.3 **FOC Control**- FOC (Field-Oriented Control) also called vector control [3]. FOC gives very high-power output. It is very good at outputting high power, maximum torque, and maximum power into the motor. It also gives very low noise. An FOC implementation gives the best noise performance, even compared to a sinusoidal algorithm. FOC has the best torque ripple. It can adapt to changes in torque much better than sinusoidal control. It can achieve a very high motor speed. FOC classically has the

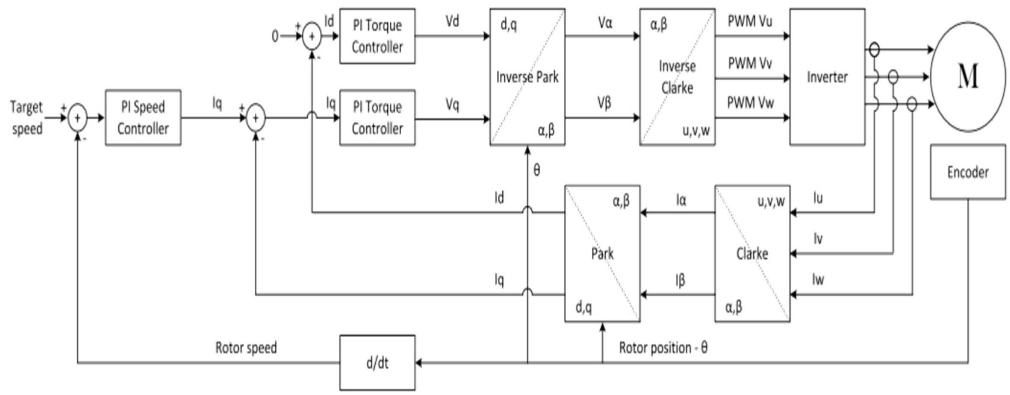

Fig.1.9: FOC Control

highest efficiency. The disadvantages are High Switching losses and computation complexity. The Fig 1.9 shows the circuit diagram of FOC Control.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The publication [1-3] describes about the fundamentals of Brushless DC Motor which gives the basic idea of working and laws on which this motor runs. And also compares this motor with other motors. Also describes the advantage and disadvantage of using different methods.

G. Tatar et al. [4-11] represents the speed control of BLDC motor as well as the dynamic analysis and the modelling of the motor. The simulation shows the speed control of the motor. The paper [5] shows the speed control of motor using hall sensor. In this BEMF of the motor is collected in the battery. Hence the generated energy can be stored and reused.

The researches [12-22] emphases upon the FOC control (space vector PWM control) and the Sinusoidal PWM control of VSI of the permanent magnet synchronous motor (PMSM). The Field-oriented control (FOC) of PMSM is extensively preferred in system due to its different features like high efficiency, better power factor and high torque. Paper [13] shows the controlling strategy with a new topology based on a capacitor and battery so that unstable voltage can be regulate. Paper [15] characterizes the control of PMBLDC motor using instrumentation technique. This also deals with the speed control of motor using FPGA.

M. Purnalal1, et al. [23-25] presents a Modelling and performance of BLDC motor using PID controlled and different proposals of PWM control of BLDC motor. Hence the main focus is upon modelling to highlight the effectiveness of speed control. Here Ziegler-Nichols tuning method is taken to control the PID controller. And paper [26-27] represents the speed torque characteristics of BLDC.

As a BLDC motor is a sort of synchronous motor and this motor provides linear relationship between voltage to rpm and current to torque. This characteristic offers a brilliant option to use the BLDC motor in ceiling fans. Hence the paper [28] presents a BLDC fan with 3 different modes of operations. These modes are manual mode, remote control mode and auto mode.

A. Thomas et al [29] represents a relative study of cost and performance of 3-phase PM BLDC motor for ceiling fan on the basis of different material used for the rotor which is bonded NdFeB and ferrite magnets. It is shown that while the mass of ferrite motor is around 1.47 times that of bonded NdFeB motor, but total expenditure of the motor is about 77.8% that of bonded NdFeB motor.

As using Trapezoidal control or 120-degree conduction mode there are some finite torque ripples. To overcome this there is a method named sinusoidal pulse width modulation control or 180-degree conduction mode. The paper [30] represents Modified sinusoidal pulse width modulation which reduces the torque ripple up to 50%.

The publications [31-32] deals with the PFC based CUK converter fed BLDCM fan and performance has been analysed in 4 distinct modes of operation in CCM and DCM. The study shows that CUK converter with output inductor current operating in DICM is best working mode.

V. Bist et al. [33-34] presents the working of unity PF bridgeless isolated CUK converter-based BLDC which eliminated the use of DBR hence, the conduction losses. There is another control strategy for BLDCM is considered that consists current modulation [33].

The AC-DC PFCC brushless motor fan using SEPIC is presented in DCM mode [35] with high-frequency transformer with improved power quality. This topology provides low harmonic distortion and lesser losses with reduced fan cost due sensorless technique.

The paper [36] analyses the behaviour of ceiling fan based on bridgeless-isolated PFC SEPIC converter in DCIM mode. This also uses a HFT which provides isolation in the system. The isolated SEPIC [33] based power supply gives excellent power quality at both input and output side. This also provides fast dynamic response, small size and less no. of components with high degree of reliability and efficiency.

The system based on single switch boost- flyback converter [37-38] reduces the voltage sensor so reduces the cost of fan. The isolated converter HFT provided simple control, lower component count and isolation [33]. One more topology of flyback converter, that is single stage bridgeless flyback (SSBL- Flyback) has been analysed. This can reduce conduction losses.

Some research has also been done on PFC buck-boost converter [39-40] for ceiling fan. This topology has less no. of components so it is a cost-effective solution for system having low power.

Publication [41-42] analyses the performance of ceiling fan circuit using PFC zeta converter in DCM mode. This power supply uses high-side switch and gives the protection from inrush currents, overload and short-circuit. these power supplies are also used in high power application. Zeta converter also exhibits the continuous current on both input and output side.

There are various other converter topologies [50], [51] investigated such as a BL-CSC converter (Bridgeless canonical switching cell) [43] for low power applications. Another is Bridgeless Luo converter [44-45] which works in DICM that perform as inherent PF pre-regulator and the other one is Bridgeless Landsman converter [46] that works well for adjustable speed applications. A non-isolated-based single-stage integrated bidirectional converter [47] has been proposed.

Electromagnetic interference (EMI) filter is utmost enhanced solutions to have EMI elimination. To lessen the weight and size of these filters, this paper [48-49] suggests a multi-function common mode choke (MCMC) used in EMI filter.

Conclusions

In the present chapter different methods, speed control and the various converter topologies with power factor correction has been mainly represented. Together with this, modelling of motor as well as the advantage of material used for rotor has also been described.

Generally, the people favour to use an induction motor ceiling fan and it spends around 75W. But in the present situation BLDC fans are emerging solution which consumes very less power.

Hence, this thesis mainly aims to represent the difference consequences while designing the BLDC motor fans. Therefore, the thesis is presenting the different methods, different converter topologies as well as power factor correction of the motor. Along with this the THD in input current which satisfy the IEC standard 61000-3-2. And the performance and power quality of BLDCM ceiling fan under different input supply and different DC voltage.

CHAPTER 3

SPEED CONTROL OF BLDCM

3.1 Introduction

BLDC motors are the electronically commuted motor and these are gaining popularity mainly because of its performance and characteristics as compared to other motors. So as this motor provides better efficiency, there are many researches going on to improve the controlling scheme of this motor whether operating with dc or ac. This motor works by energizing the stator winding in a sequence according to the hall sensor detects the rotor position. There is no any contact in between stator and rotor. So, the current sequence in the stator is decided by the switches connected in the voltage source inverter.

The BLDC motor [8-11] works more efficiently and accurately as this is operated by semiconductor switches. Specially with the improvement in computer science technology, BLDC performance is continuously improving as computer programming can increase the computational abilities of the design such as complex modelling of motor,

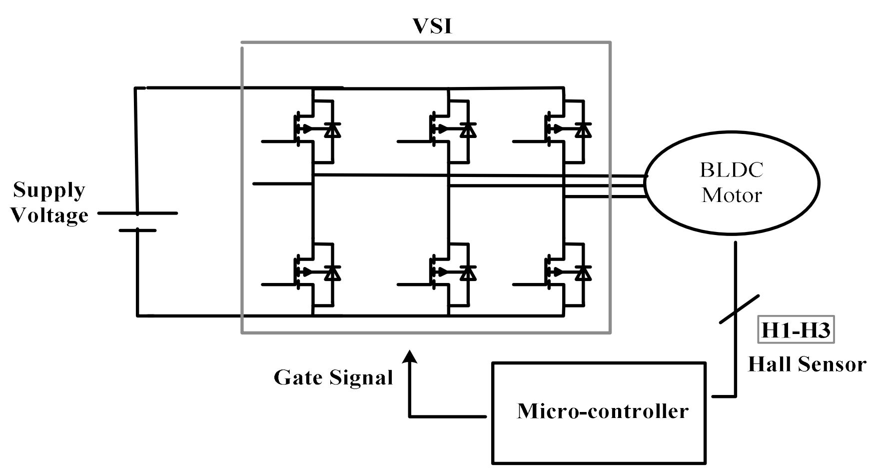

Fig.3.1: Circuit diagram of the 3-phase BLDC motor.

mathematical equations. This motor is of 1 phase and 3 phase. The mostly used motor is 3 phase BLDC motor. The working of the BLDC motor can be seen using MATLAB below.

3.2 Speed control of BLDC

During the operation, the stator winding of motor generates the voltage, which is called BEMF. This emf counters the main voltage according to Lenz's law. Various factor determines this Back-EMF [4-7] such as-

(1) Angular velocity of the moto, (2) no. of turns in the stator windings, (3) Magnetic field produced by magnets of rotor.

When the motor rotates, the magnetic field of the rotor and the no. of turns in the winding remain constant but the angular velocity varies. Hence, the BEMF depends upon this angular velocity or we can say the rotor speed as shown in Fig3.1. So, as the speed of the motor rises, the BEMF also rises. Therefore, DC supply Voltage should be adequate to draw the rated current and run the motor successfully.

3.3 Motor Parameters

Table 3.1 Motor Parameters

Motor Parameters	**Rated Values**
Rated Voltage	48V
Rated Torque	1 N-m
Winding Resistance	4Ω
Winding Inductance	10.75mH
Rotor Poles	16
Speed	350 rpm
V_k	$127V_{pk}$/krpm

3.4 Simulation and results

The dc voltage is applied to the switches of voltage source inverter. The Simulink model in Fig 3.2 consists VSI, hall- sensor decoder which converts the hall sensors position into gate signal required for VSI.

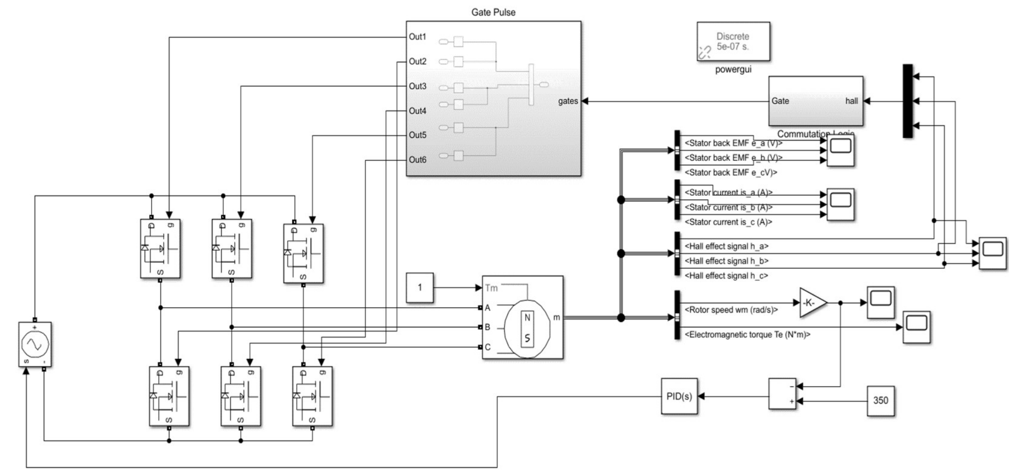

Fig.3.2: MATLAB simulation of speed control of BLDC Motor

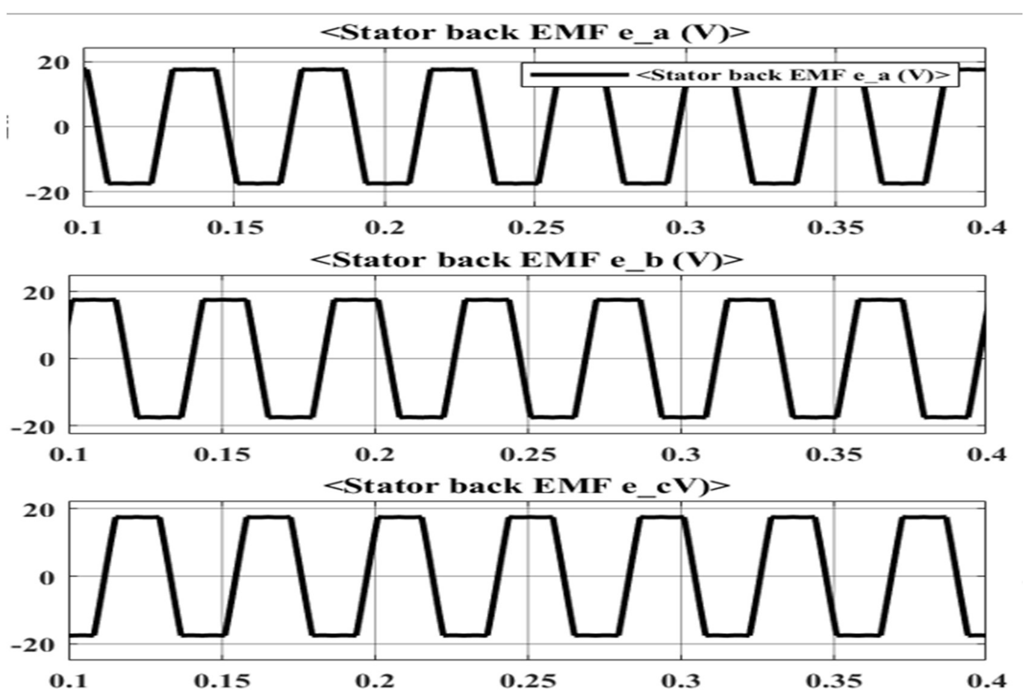

Fig.3.3: BEMF waveforms

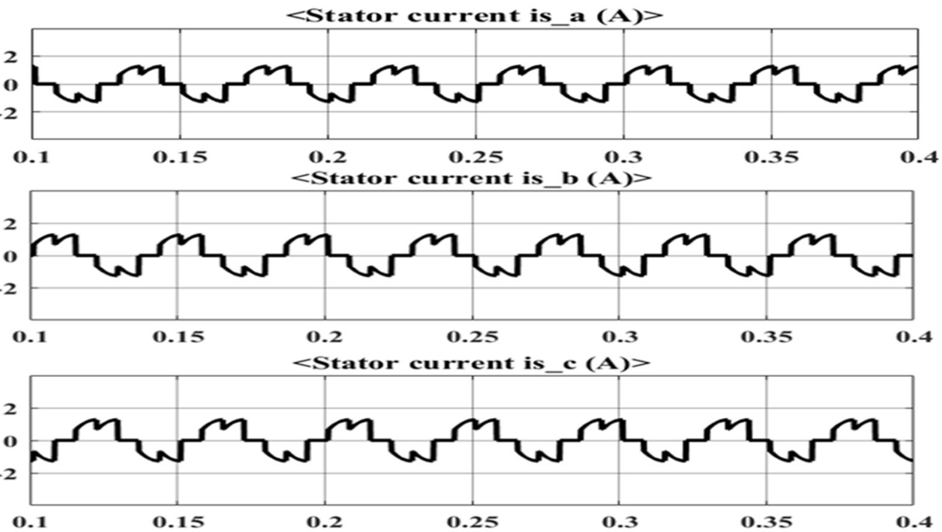

Fig. 3.4: current waveform

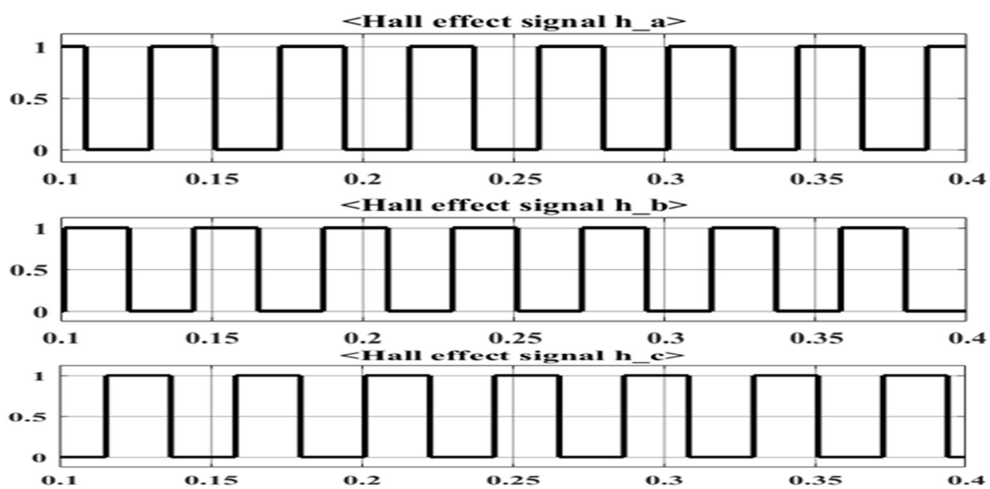

Fig.3.5: Hall-sensor waveform

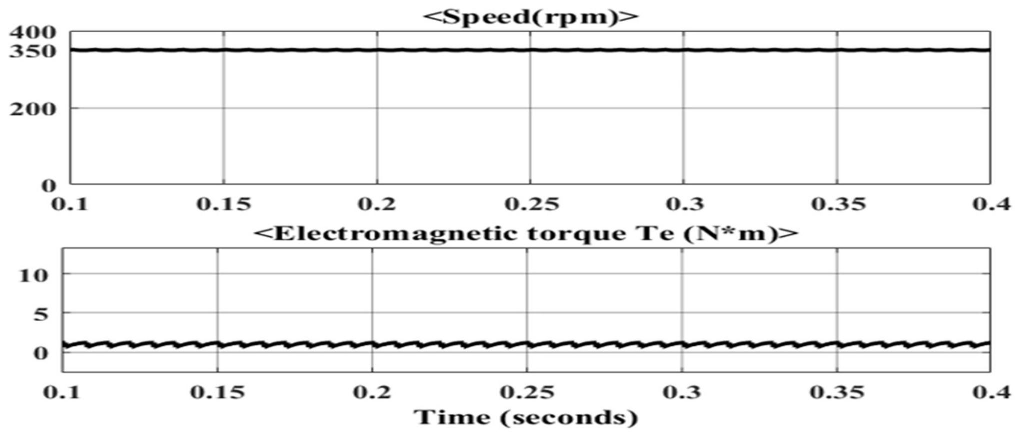

Fig3.6: speed and Torque

3.5 Summary

The study discusses the speed control of BLDC motor using PI controller. And also determines the factor on which BEMF depends. The simulation also shows the results as shown in Fig 3.3 BEMF waveforms, Fig. 3.4 current waveform, Fig. 3.5 Hall-sensor waveform and Fig. 3.6 speed and Torque waveform using MATLAB

CHAPTER 4

SIMULATION OF BLDC CONTROL METHODS FOR THE APPLICATION OF FAN

4.1 Block diagram of BLDC Motor Fan-

The block diagram of the BLDC motor fan can be seen here in Fig 4.1.

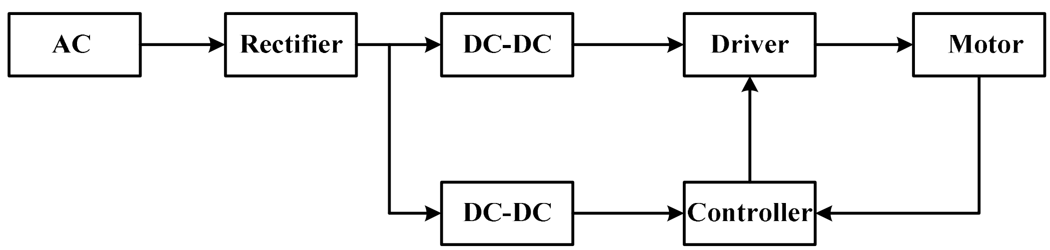

Fig.4.1: Block Diagram of working of BLDC by AC supply

4.2 DC-DC converter-

Here, buck-converter as in Fig 4.2 is taken for simulation. This is used to step-down the voltage which are converted into DC from AC supply. The buck converter is also termed as the step-down converter as this step down the voltage by storing the energy in inductor while the switch is turned on and while the switch turned off, the voltage appears across output by suitable duty cycle.

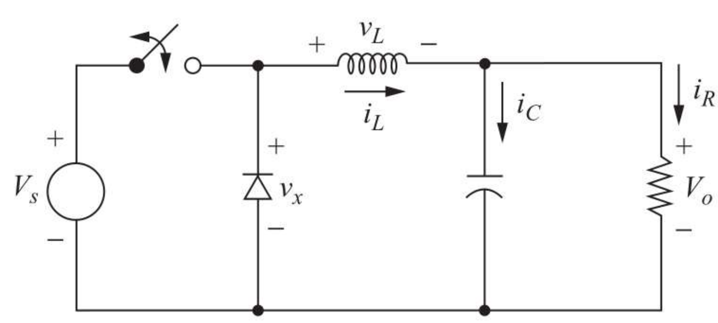

Fig.4.2: Buck-converter

4.3 Working- Fig 4.3 shows the working of BLDC fan. As from the supply, we get 90-285v AC voltage. This input voltage is given to the rectifier to get the DC voltage from the AC supply as the motor works on DC and the capacitor is used here to get the peak voltage. This DC voltage is further step-down to 24V DC by using Buck converter. This 24V DC is given to the driver circuit as a supply. And one Buck converter is also used for the supply of microcontroller, which step down the voltages into 5 or 3.3v according to the need of microcontroller. The signal generated by hall sensor is fed to Microcontroller which sends switching pulses to driver circuit according to the rotor position and speed. So, after getting pulses from the Microcontroller, the switches of driver circuit magnetize the field winding of the motor. And according to the field winding, rotor of the motor rotates.

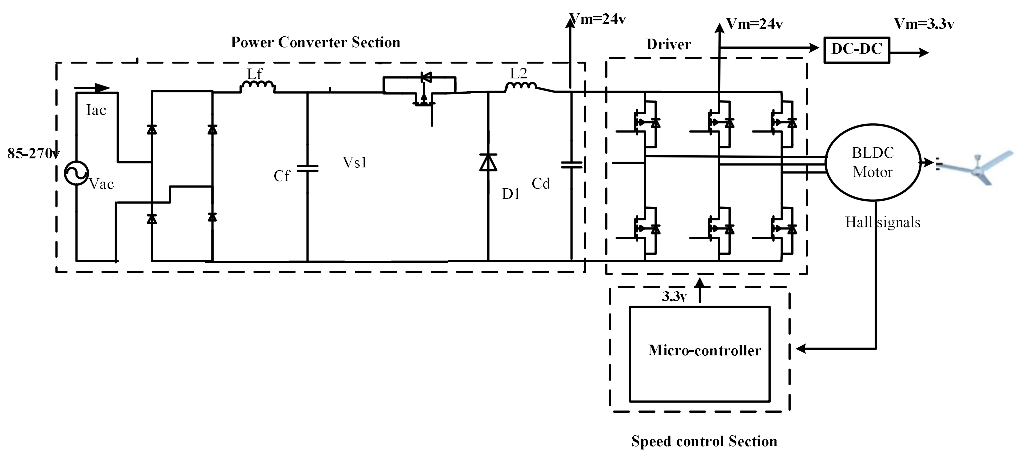

Fig.4.3: Circuit diagram of working of BLDC Motor FAN

4.4 Trapezoidal and FOC methods-

4.4.1 Trapezoidal Method- this method works [18-22] only when there are hall sensors mounted on the stator of the motor. Here BEMF is across two terminal of the field and while the third one terminal is electrically disconnected. The current also follows the BEMF shape. Thus, a set of steps from zero position to positive, then to zero, and again to negative. These motor applications for example air conditioners and refrigerators use of Hall-Effect sensors not a viable option.

4.4.2 FOC Control- This driving method [12-17] includes measurement of stator phase-currents as well as the speed of the motor. Here the motor current is taken into account which depends upon speed and time. These currents are converted into 2-coordinate time independent quantities by using Clarke and Park transformation. Which are called Id and Iq. The transformed quantities are equated with the reference values of currents. The Id component of current is made to zero as to maximize the Torque and these are given to PID controllers. The output of the PID controllers in line selects the switch position of Mosfets in the VSI to run the motor.

4.5 Analysis of the methods

Depending on the application, these methods can be used. For example, in the case of fan if less noise during running of fan is required then sinusoidal method should be used, if maximum torque is required then FOC method should be used and if we want the cost-efficient fan then trapezoidal method should be used. Table 4.1 shows comparison of these 3 methods.

Table 4.1 Comparison of methods

	Trapezoidal Method	**Sinewave Method**	**FOC**
Torque Ripple	High	Low	Lowest
Torque	Not Smooth	Smooth	Smooth
Efficiency	High	Good	Best
Noise	High	Low	Lowest
Power Output	Low	High	Highest
Switching losses	Low	High	High
BEMF calculation Complexity	Easy	Tough	Tough

Dynamic Load Performance	Good	Not good	Best
Sense	Hall Sensor /BEMF	Hall Sensor /BEMF	BEMF/Current
BEMF sense	Comparator	BEMF equation	BEMF equation
BEMF calculation	Measureme nt	Estimation/ Calculation	Estimation/ Calculation

4.6 Dynamic modelling of BLDC motor

Modeling for BLDCM can be done as 3-ph induction motor as in Fig 4.4. The stator winding of BLDCM can be represented as [23-25]-

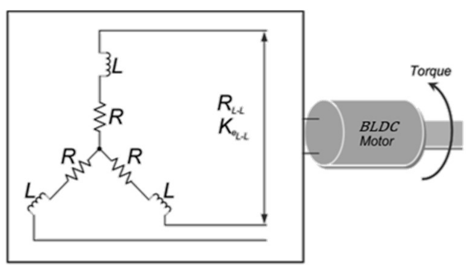

Fig.4.4: Dynamic Modelling of Motor

The equations for 3-phase motor, obtained from the equivalent circuit are-

$$V_{an} = R_s + L.\frac{di_a}{dt} + M.\frac{di_b}{dt} + M.\frac{di_c}{dt} + E_a \quad (4.1)$$

$$V_{bn} = R_s + L.\frac{di_a}{dt} + M.\frac{di_b}{dt} + M.\frac{di_c}{dt} + E_b \quad (4.2)$$

$$V_{cn} = R_s + L.\frac{di_a}{dt} + M.\frac{di_b}{dt} + M.\frac{di_c}{dt} + E_c \quad (4.3)$$

Where,

L is self-inductance [H] of armature,

M is mutual inductance [H] of armature,

R is armature resistance [Ω],

V_{an}, V_{bn}, V_{cn} are terminal phase voltage [V],

i_a, i_b, i_c are motor input current [A],

E_a, E_b, E_c are motor's BEMF [V]

$$\text{Ea} = K_e \omega f(\theta) \tag{4.4}$$

$$\text{Ea} = K_e \omega f\left(\theta - \frac{2\pi}{3}\right) \tag{4.5}$$

$$\text{Ea} = K_e \omega f\left(\theta + \frac{2\pi}{3}\right) \tag{4.6}$$

Where, K_e is the voltage constant of motor in (Volt/ rad.s^{-1}),

θ is rotor position angle,

ω is angular speed (rpm) of the motor,

$f(\theta)$ is BEMF function of rotor position.

In matrix form,

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} Rs & 0 & 0 \\ 0 & Rs & 0 \\ 0 & 0 & Rs \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix}$$

$$V_{an} = R_s + L.\frac{di_a}{dt} + M.\frac{d(i_b + i_c)}{dt} + E_a \tag{4.7}$$

$$V_{an} = R_s + L.\frac{di_a}{dt} - M.\frac{di_a}{dt} + E_a \tag{4.8}$$

$$V_{an} = R_s + (L - M).\frac{di_a}{dt} + E_a \tag{4.9}$$

$$V_{an} = R_s + L_s.\frac{di_a}{dt} + E_a \quad (4.10)$$

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} Rs & 0 & 0 \\ 0 & Rs & 0 \\ 0 & 0 & Rs \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + Ls \begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad (4.11)$$

$$\begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} = \frac{1}{L_s} \left\{ \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} - \begin{bmatrix} Rs & 0 & 0 \\ 0 & Rs & 0 \\ 0 & 0 & Rs \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \right\} \quad (4.12)$$

The output power can be calculated as,

$$P_m = E_a.i_a + E_b.i_b + E_c.i_c \quad (4.13)$$

$$T_e = \frac{E_a.i_a + E_b.i_b + E_c.i_c}{\omega_r}.\frac{P}{2} \quad (4.14)$$

$$T_e = \frac{(K_a.i_a + K_b.i_b + K_c.i_c)Wr}{\omega_r}.\frac{P}{2} \quad (4.15)$$

$$T_e = \frac{(K_a.i_a + K_b.i_b + K_c.i_c)}{2}P \quad (4.16)$$

The equations for the mechanical part can be represented as

$$T_e - T_L = J.\frac{d\omega_{rm}}{dt} + B\omega_{rm} \quad (4.17)$$

$$T_e = T_L + J.\frac{d\omega_r}{\frac{P}{2}dt} + \frac{B\omega_r}{\frac{P}{2}} \quad (4.18)$$

$$\frac{d\omega_r}{dt} = \frac{P}{2J}\left(T_e - T_L - \frac{2B.\omega_r}{P}\right) \quad (4.19)$$

4.7 Motor Specifications

Table 4.2 Motor Parameters

Motor Parameters	Rated Values
Rated Voltage	48V
Rated Torque	0.65 N-m
Winding Resistance	4Ω
Winding Inductance	10.75mH
Rotor Poles	16
speed	340 rpm
V_k	$127V_{pk}$/krpm

4.8 Calculations-

The supply voltage for the DBR is-

$$\text{Vin} = \frac{2\sqrt{2}.\text{Vm}}{\pi}\sin(\omega t) \tag{4.20}$$

Where, V_m is Maximum of supply voltage.

The average voltage of the DBR is-

$$\text{Vin} = \frac{2\sqrt{2}\times 230}{\pi} = 207.18V \tag{4.21}$$

The peak (or max) voltage is-

$$\text{Vm} = \sqrt{2}\times 230 = 325V \tag{4.22}$$

The inductor of Buck converter is-

$$L = \frac{(Vs - Vo)D}{\Delta i.f} \tag{4.23}$$

$$L = \frac{(325-48)0.147}{0.1\times 0.73\times 20K}$$

$$L = 27.88mH$$

The capacitor of Buck converter is-

$$C = \frac{1-D}{8 \times L \times \left(\frac{\Delta V_0}{V_0}\right) \times f^2} \tag{4.24}$$

$$C = \frac{1-0.147}{8 \times 20.88m \times (0.02) \times (20K^2)}$$

$$C = 0.638\mu F$$

4.9 Filter design calculation

The electromagnetic interference (EMI) filter is designed to remove the harmonics at the input current. The values for the capacitor can be taken as-

$$Cfmax = \frac{Ipk}{W.Vm}\,tan\theta \quad and \quad Cf \ll Cfmax \tag{4.25}$$

$$Cfmax = \frac{\sqrt{2} \times \frac{35}{230}}{125.6 \times 325} tan1° = 92.02nF$$

4.10 Simulation and Results

The performance of BLDCM fan can be seen using MATLAB Model in Fig 4.5 and Fig 4.9 by Trapezoidal and FOC Method.

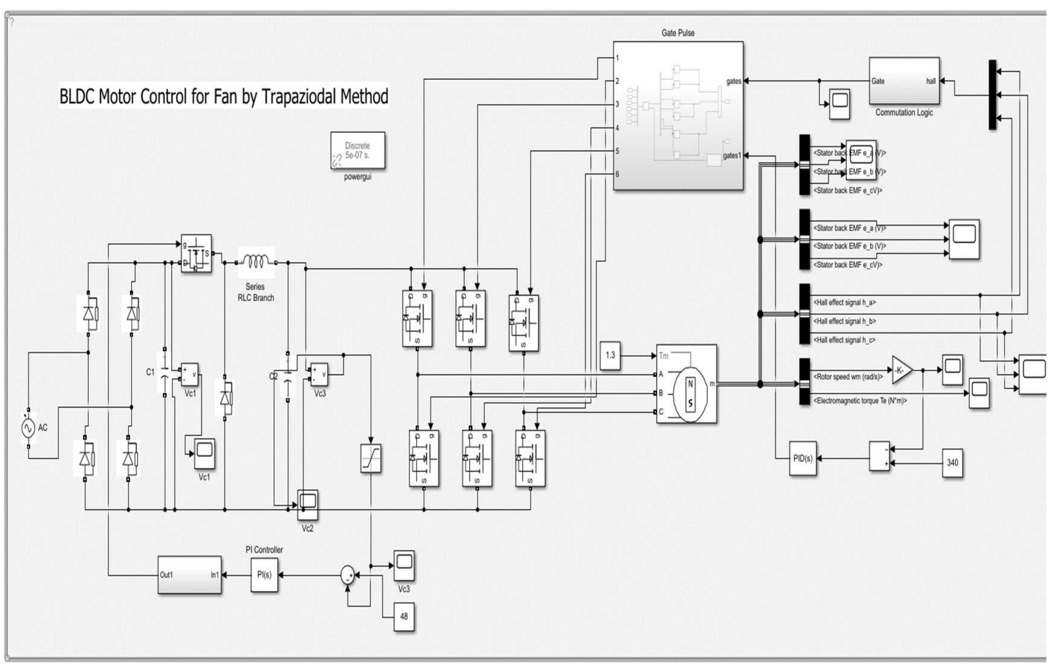

Fig.4.5: Simulation of BLDC motor control by Trapezoidal Method

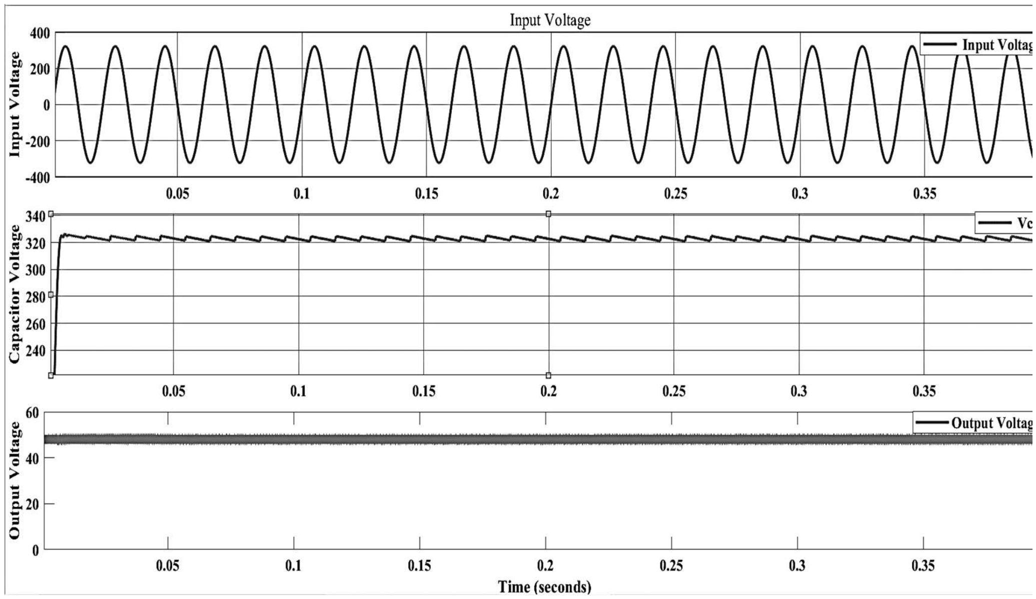

Fig 4.6: Input supply, capacitor voltage and converter output voltage

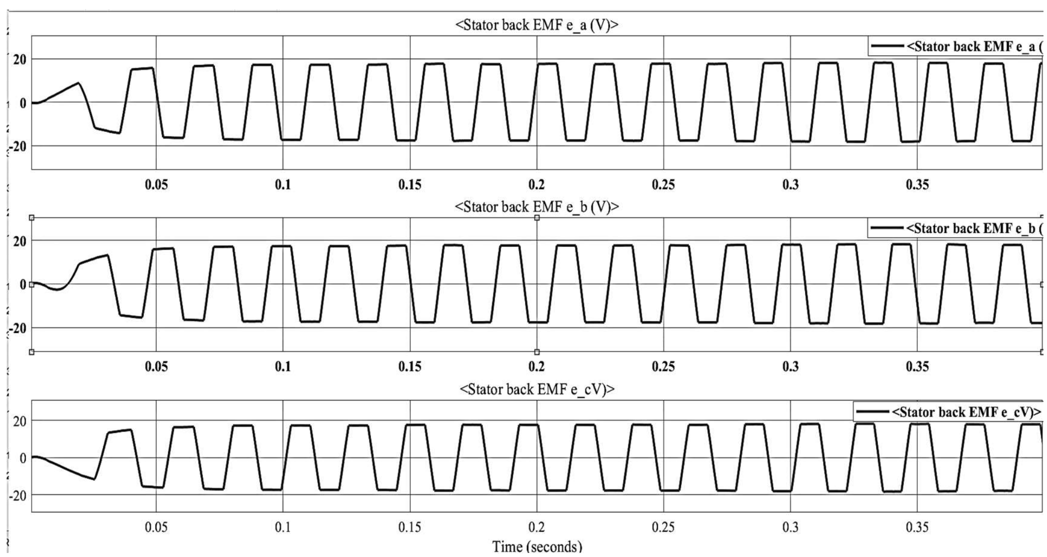

Fig 4.7: BEMF

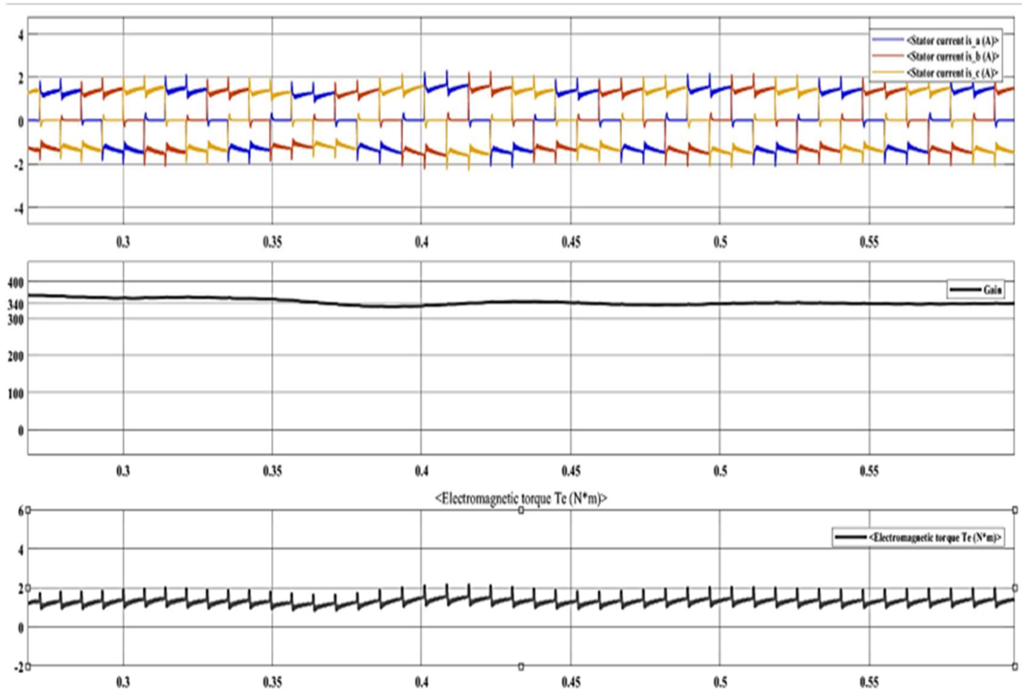

Fig.4.8: Current, Speed and Torque

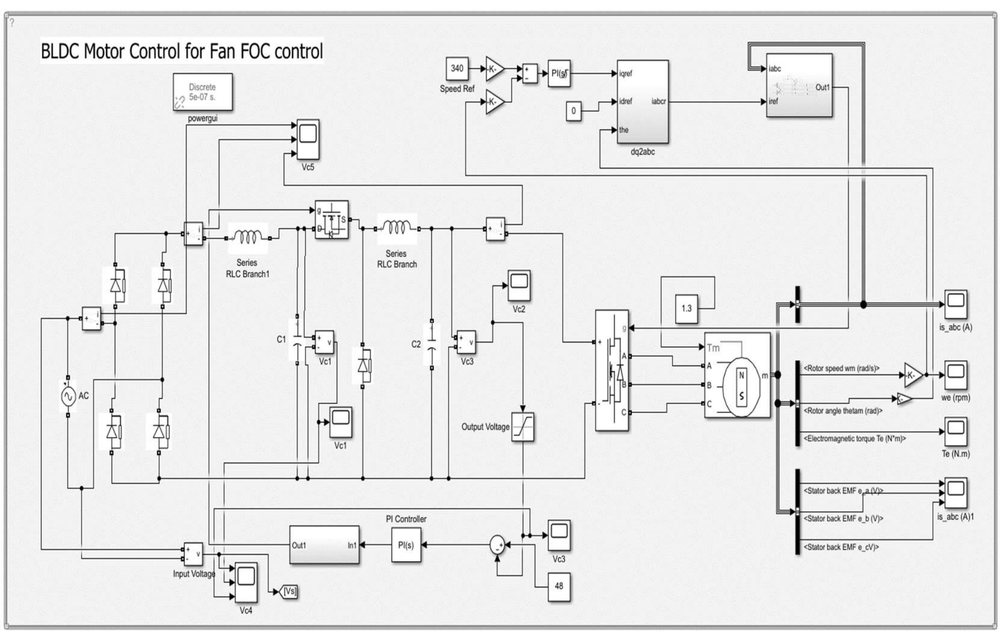

Fig.4.9: Simulation of BLDC motor control by FOC Method

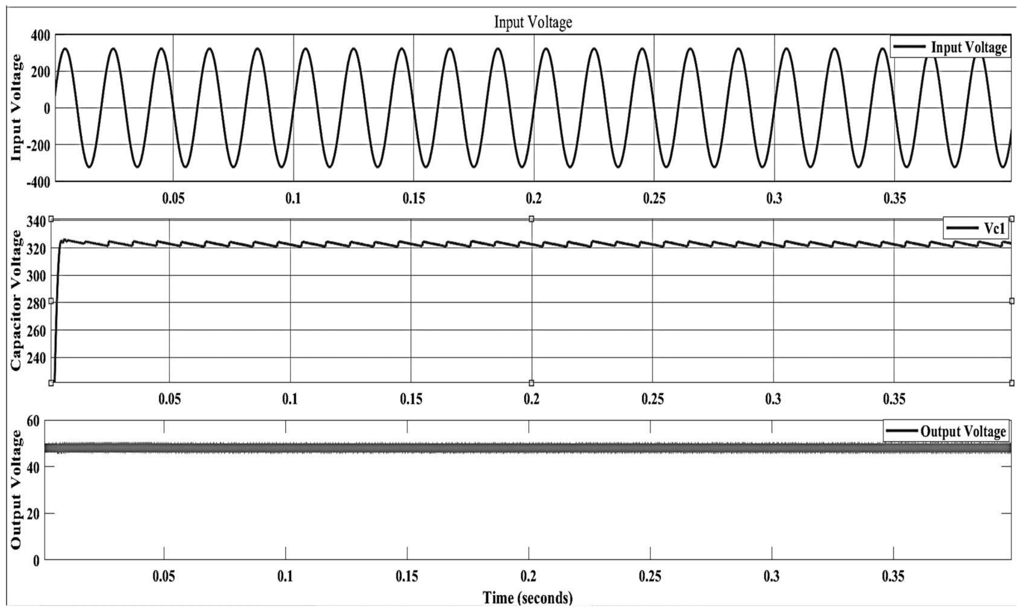

Fig 4.10: Input supply, capacitor voltage and converter output voltage

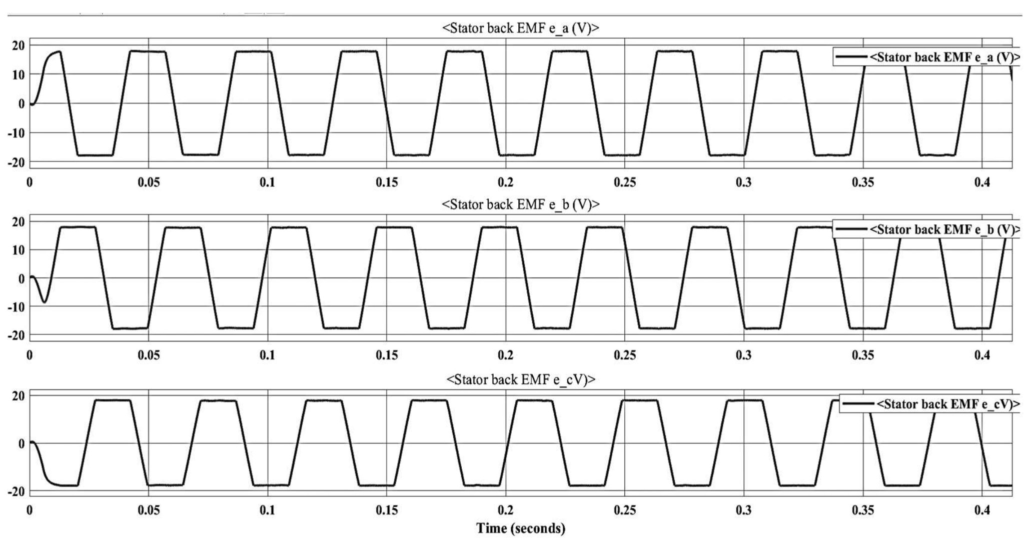

Fig 4.11: BEMF

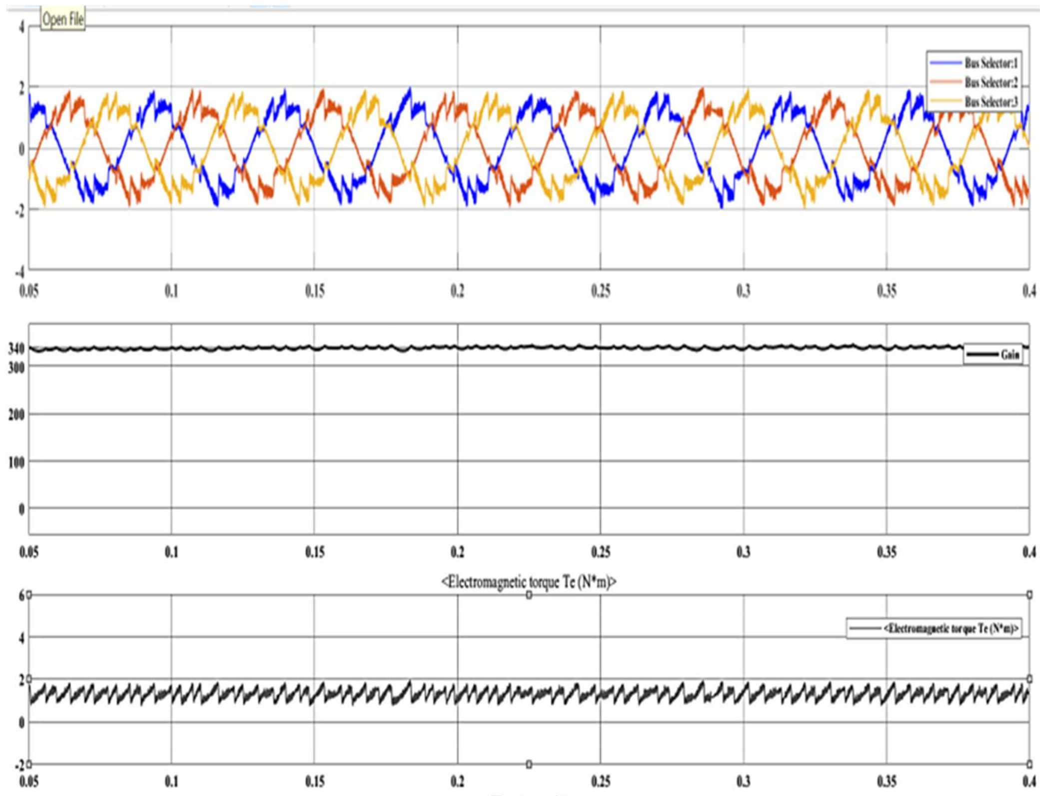

Fig.4.12: Current, Speed and Torque

4.11 Summary

In this chapter, the study has been done regarding overall working when we connect the motor with AC supply, the use of buck converter as DC-DC converter to step down the voltage. The difference between trapezoidal method and FOC method has been discussed and the MATLAB results of these methods have also been observed. Fig 4.6 shows the Input supply, capacitor voltage and converter output voltage, Fig 4.7 shows BEMF and Fig.4.8 shows Current, Speed and Torque by Trapezoidal method. Fig 4.10 shows the Input supply, capacitor voltage and converter output voltage, Fig 4.11 shows BEMF and Fig.4.12 shows Current, Speed and Torque by FOC method

Chapter 5

PFC Isolated CUK converter based BLDCM

5.1 Overview of Isolated CUK Converter

The 1-phase AC-DC buck–boost [37-40] converters are usually favored and these are suitable for low-power applications, which is less than 500 W. CUK converters are the also derived from the buck- boost converter and they also provide the almost same characteristics as buck-boost.

Here, the transformer helps to provide multiple outputs as well as the isolated converter with high frequency transformer enables isolation, better control and electrical safety. The isolated CUK converter also shows the excellent power quality at both the input as well as output side.Generally, the energy is conveyed through inductors but in this topology, the energy is moved with the help of capacitors. Hence both the current (input and output side) are continuous and the ripple in both input and output currents are

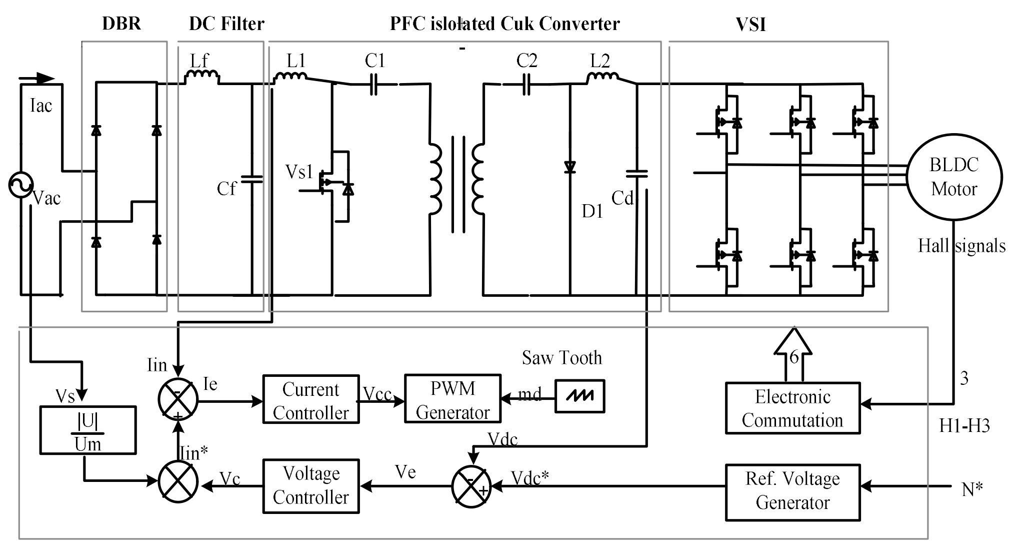

Fig.5.1: A BLDC Motor drive fed by a PFC Isolated Cuk converter in CCM (using a current multiplier approach).

lesser than the other converters [31-36]. This design provides wide range of input and output voltage, very low switching current ripple, small size, high overall conversion efficiency and natural protection against inrush current so, this design is a popular choice for use [2]. Fig 5.1 demonstrates the complete working of Isolated CUK PFC converter based Sensored BLDC motor fan.

5.2 PFCC design

This PFC converter is intended for output voltage of 48V and the input power of 30W specifications. Here, the switching is taken as 200kHz so that it reduces the inductor size. This converter works in CCM (continuous current mode) so a current controller is also used in close loop. This PFCC [41-45] improves the power factor as well as the THD. With the change is output voltage of this converter, the speed of the BLDC motor changes so the fan speed can be controlled.

According to the variation is domestic power supply, the voltage variations are considered (or taken) as- 85V (Vmin) to 270V (Vmax) and the DC link voltage from 10V (VDC(min)) to 48 (VDC(max)) respectively.

5.3 Calculation

The values for the PFC converter can be taken according to design equations-

The supply voltage for the DBR is-

$$V_{in} = V_m . \sin(\omega t) \tag{5.1}$$

Where, V_m is peak of supply voltage.

The average voltage of the DBR is-

$$V_{in} = \frac{2\sqrt{2}.V_m}{\pi} \sin(\omega t) = 198.07\ V \tag{5.2}$$

The peak (or max) voltage is-

$$V_m = \sqrt{2}. V_{in} = 311\text{V} \tag{5.3}$$

The peak voltage according to 85V (V_{min}) and 270V (V_{max}) will be 120.21V and 381.83V respectively.

The DC link voltage (V_{dc}) is taken 48V according to motor requirement.

Hence, the output voltage can be calculated by,

$$V_{dc} = \frac{D}{(1-D)} \times \frac{N_2}{N_1} \times V_m \quad (5.4)$$

Here, N_2/N_1 is the Transformer (HFT) turns ratio which is considered as 0.5 for the calculation.

Hence, the duty ratio required for the system is,

$$D_{min} = \frac{V_{dc}}{V_{dc} + (V_m)_{max}\left(\frac{N_2}{N_1}\right)} \quad (5.5)$$

$$D_{min} = \frac{48}{48 + \sqrt{2} \times 270 \times 0.5} = 0.2009$$

$$D_{nom} = \frac{V_{dc}}{V_{dc} + (V_m)_{nom}\left(\frac{N_2}{N_1}\right)}$$

$$D_{nom} = \frac{48}{48 + \sqrt{2} \times 220 \times 0.5} = 0.2358$$

$$D_{max} = \frac{V_{dc}}{V_{dc} + (V_m)_{min}\left(\frac{N_2}{N_1}\right)}$$

$$D_{max} = \frac{48}{48 + \sqrt{2} \times 85 \times 0.5} = 0.4440 \quad (5.6)$$

The min, nominal and max duty ratio are 0.2009, 0.2358 and 0.4440 respectively.

The converter is design to operate in CCM, So the value for inductor (input side) can be calculated by considering 40% ripple in current as-

$$L_1 = \frac{V_s D_{max} T_s}{\Delta i_{L1}}$$

$$= \frac{V_s^2 V_{dc} T_s}{\Delta i_{L1} \times P_{in} \times (n(V_m)_{min} + V_{dc})} \quad (5.7)$$

$$L_1 = \frac{85^2 \times 48 \times 5 \times 10^{-6}}{0.4 \times 30 \times (0.5 \times \sqrt{2} \times 85 + 48)} = 1.33mH$$

Taking switching frequency as 200kHz, the designed value of inductor is selected as 1.4mH so that it will work in CCM.

The load resistance and input side capacitance of the converter is-

$$R_{dc} = \frac{V_{dc}^2}{P_{in}} = \frac{48^2}{30} = 76.8\Omega \tag{5.8}$$

$$C_1 = \frac{V_m n^2 D_{min}^2}{\Delta V_{c1} f_s R_{dc}(1 - D_{min})} \tag{5.9}$$

$$= \frac{220 \times \sqrt{2} \times 0.2009 \times 0.5^2}{0.1 \times (\sqrt{2} \times 220 \times 0.5 + 48)200000 \times 76.8 \times (1 - 0.2009)}$$

$$C_1 = 12.55nF$$

The designed value of C_1 is selected as 15nF and the voltage ripple are considered as 10%

The magnetizing inductance of HFT can be calculated by the following equation-

$$L_m = \frac{(1 - D_{\max})^2 R_{dc}}{2n^2 f_s D_{max}} \tag{5.10}$$

$$L_m = \frac{(1 - 0.4440)^2 \times 76.8}{2 \times 0.5^2 \times 0.4440 \times 200000} = 534.72\mu F$$

The magnetizing inductance of HFT chosen as 390 μF.

The capacitor C_2 can be calculated as-

$$C_2 = \frac{P_i}{\Delta V_{dc} f_s (n.\sqrt{2}\, V_{in} + V_{dc})} \tag{5.11}$$

$$C_2 = \frac{30}{0.1 \times 48 \times 200000(0.5 \times \sqrt{2} \times 220 + 48)} = 0.15\ \mu F$$

The designed value of C_1 is selected as 0.15μF and the voltage ripple are considered as 10%.

The inductor L_2 can be calculated as-

$$L_2 = \frac{(V_{in(\min)}^2/P_{\max}) \times V_{dc(\max)}}{\Delta i_{L2} f_S \sqrt{2}\, V_{in(\min)}} \left(\frac{V_{dc(\max)}}{V_{dc(\max)} + \sqrt{2}\, V_{in(\min)}} \right) \tag{5.12}$$

$$L_2 = \frac{\left(\frac{85^2}{30}\right) \times 48}{0.4 \times 200000 \times \sqrt{2}\ \times 85} \left(\frac{48}{48 + \sqrt{2}\ \times 85} \right)$$

$$L_2 = 0.34mH$$

The output capacitor of converter can be calculated as-

$$C_{dc} = \frac{\left(\frac{Pout}{Vdc}\right)}{2\pi f \Delta V_{dc}} \tag{5 .13}$$

$$C_{dc} = \frac{\left(\frac{30}{48}\right)}{2\pi \times 50 \times 48 \times 0.02} = 1036.7\mu F$$

Here, the ripple in the capacitor voltage is considered as 2%.

The designed value of capacitor can be chosen as 1200μF.

5.4 Filter design calculation-

The electromagnetic interference (EMI) filter [48-51] is aimed to remove the harmonics at the input current. The values for the same can be taken as-

$$C_{fmax} = \frac{I_{pk}}{\omega . V_m}\, tan\theta \tag{5.14}$$

$$C_{fmax} = \frac{\sqrt{2} \times \frac{30}{220}}{2 \times 3.14 \times 50 \times 311} tan1° = 34.4nF$$

As, $C_f \ll C_{fmax}$

C_f is taken as 25nF for design and according to the value of capacitor L_f is,

$$L_f = \frac{1}{4\pi^2 f_c^2 C_f} \tag{5.15}$$

$$L_f = \frac{1}{4\pi^2 \times 100000^2 \times 25 \times 10^{-9}} = 101.42\mu F$$

f_c is chosen as, $f_l << f_c << fs$. Hence, f_c is taken as 100kHz. Where f_l is line frequency and f_c is cut-off frequency. The calculated value is selected as $150\mu F$.

Table 5.1 Motor Parameters

Motor Parameters	Rated Values
Rated Voltage	48V
Rated Torque	0.5 N-m
Winding Resistance	4Ω
Winding Inductance	10.75mH
Rotor Poles	16
Speed	350 rpm
V_k	$127V_{pk}$/krpm

5.5 Simulation and Results

Here, the performance of BLDCM fan can be seen using MATLAB results. The operations are performed under steady state and dynamic state condition. In this, the power factor and THD has been measured for different supply voltages and corresponding RMS current. And different speed according to different dc link voltage for the fan application has also been measured.

5.5.1 Steady-State Operation

Fig. 5.6 shows the low harmonic distortion in input current supply as per the IEC standard 61000-3-2 at 220V input voltage. In steady state operation, Fig.5.3 shows the waveforms of input supply Voltage, input current, DC link voltage, voltage across filter capacitor and Fig.5.4 shows the waveform of current in inductor L1, voltage across mosfet (switch), current in magnetizing winding (Lm), voltage across diode of converter. Fig.5.5 depicts the waveform of torque, hall sensor(A), back-emf (Ea), current in stator winding (Ia), speed of BLDCM (rpm).

Fig. 5.9 shows the low harmonic distortion in input current supply as per the IEC standard 61000-3-2 at 270V input voltage.

5.5.2 Dynamic Operation

Fig. 5.7 and 5.8 shows the dynamic behavior of BLDCM. In this input supply has been changed from 220 V to 270V. Fig.5.7 presents the waveforms of input supply Voltage, input current, DC link voltage, voltage across filter capacitor and Fig.5.8 depicts the waveform of torque, back-emf (Ea), current in stator winding (Ia), speed of BLDCM (rpm).

Table 5.2 BLDCM Performance for Different value of Supply Voltage

Vs(V)	I_s(mA)	PF	THD (%)
85	598.7	0.999	1.52
110	527.1	0.999	1.94
160	424.8	0.999	2.53
220	371.2	0.999	2.92
270	335.8	0.999	3.34

5.6 Modes of a Ceiling fan

The ceiling fan has different modes. Hence, speed varies according to the dc voltages of BLDCM. The table.5.3 depicts the performance of fan under different modes.

Table 5.3 BLDCM Performance for Different converter output Voltage

Vdc	Speed(rpm)	I_s(mA)	PF	THD (%)
12	80	119.5	0.988	16.03
24	160	203.0	0.995	10.03
36	260	294.4	0.998	4.69
48	350	371.2	0.999	2.92

5.7 Simulation and Results

The Simulink model of PFC Isolated Cuk Converter based BLDCM has been shown in Fig 5.2.

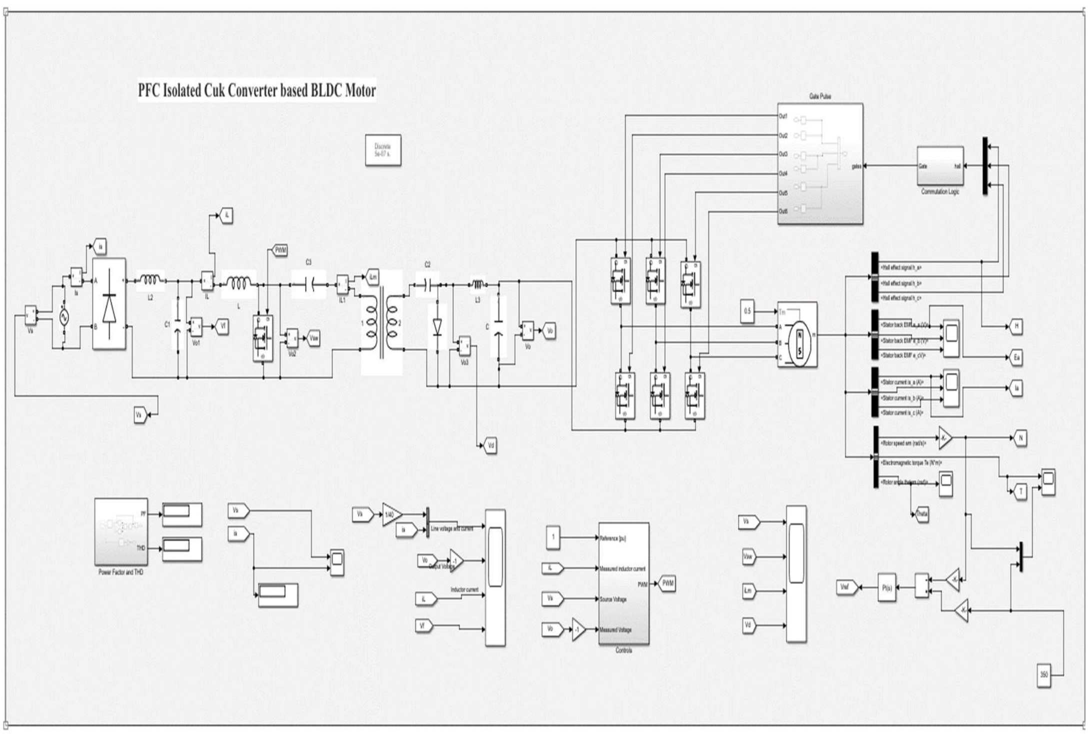

Fig.5.2: Simulation of PFC Isolated Cuk Converter based BLDCM

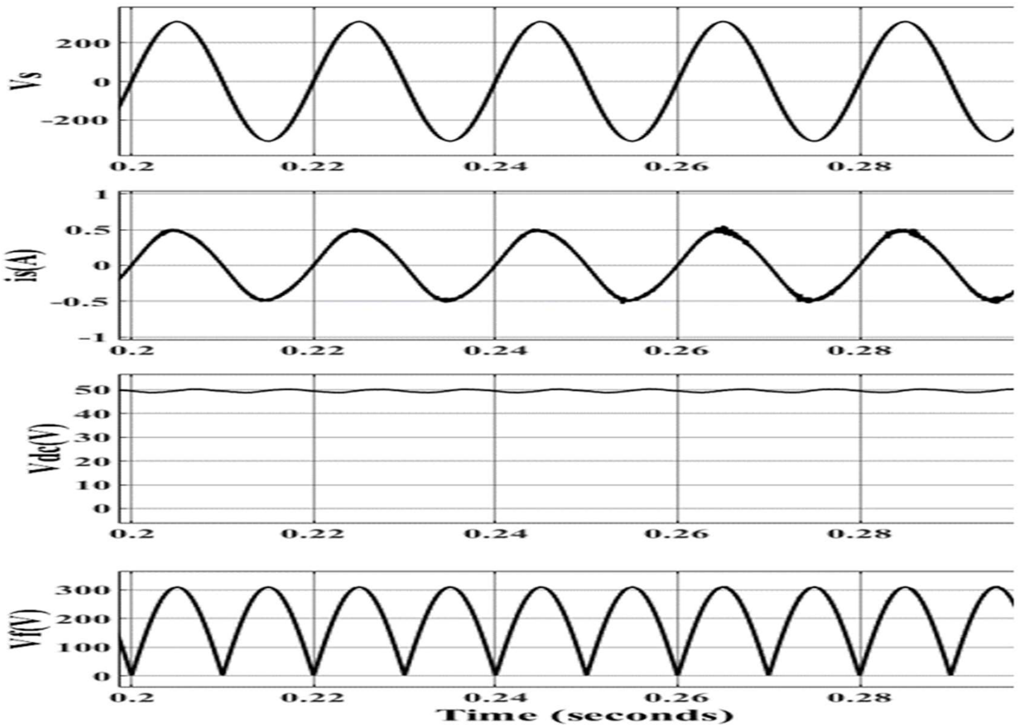

Fig.5.3: Input Voltage, Input current, Dc link voltage and capacitor filter voltage at input supply voltage of 220V and converter output voltage of 48V

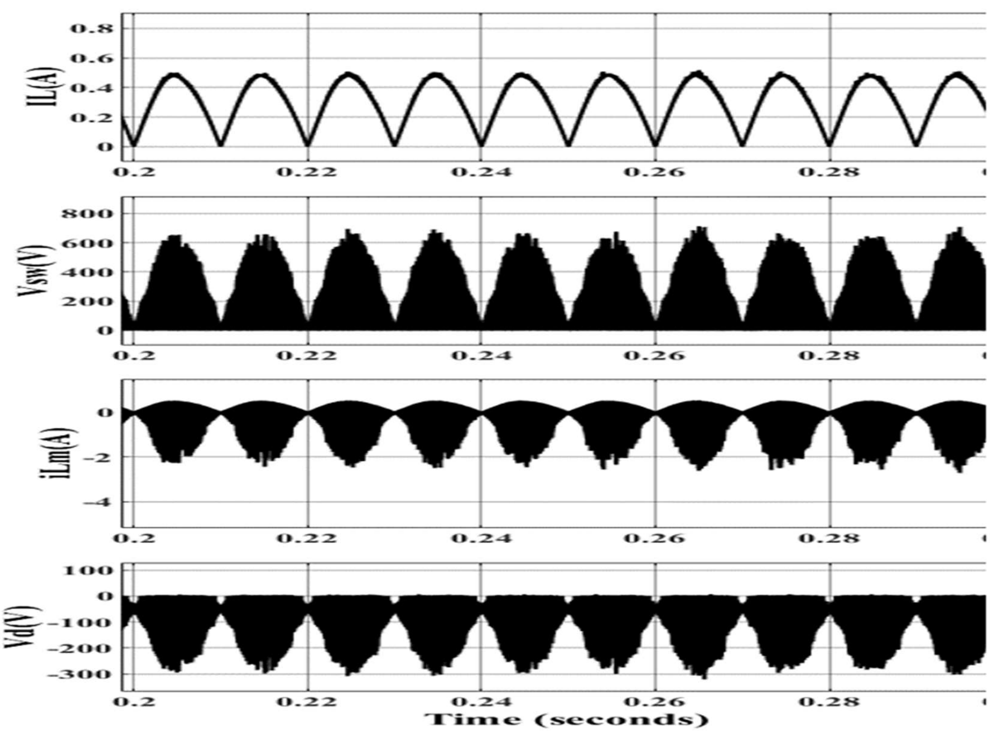

Fig.5.4: current in input side inductor of converter, voltage across switch, current in transformer winding and voltage drop across diode at input supply voltage of 220V and converter output voltage of 48V

Fig.5.5 Performance of ceiling fan under the steady state condition at input supply voltage of 220V and converter output voltage of 48V

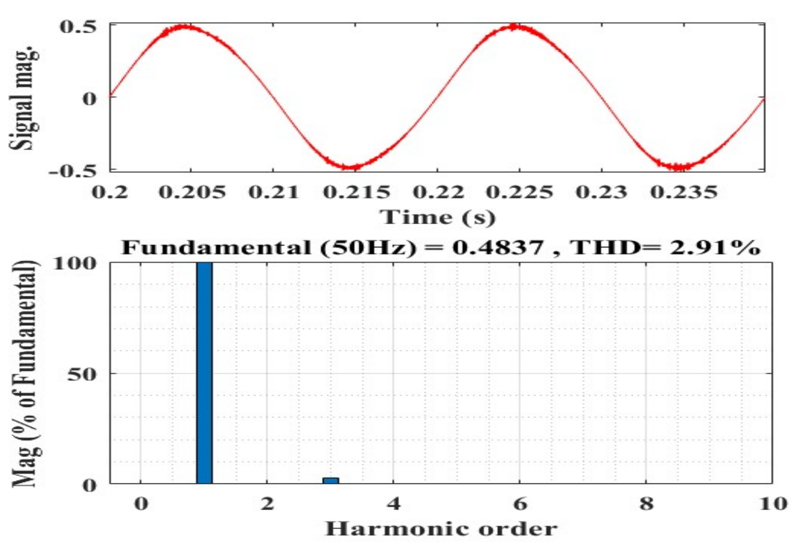

Fig.5.6: THD in supply current (RMS) at a supply voltage of 220V.

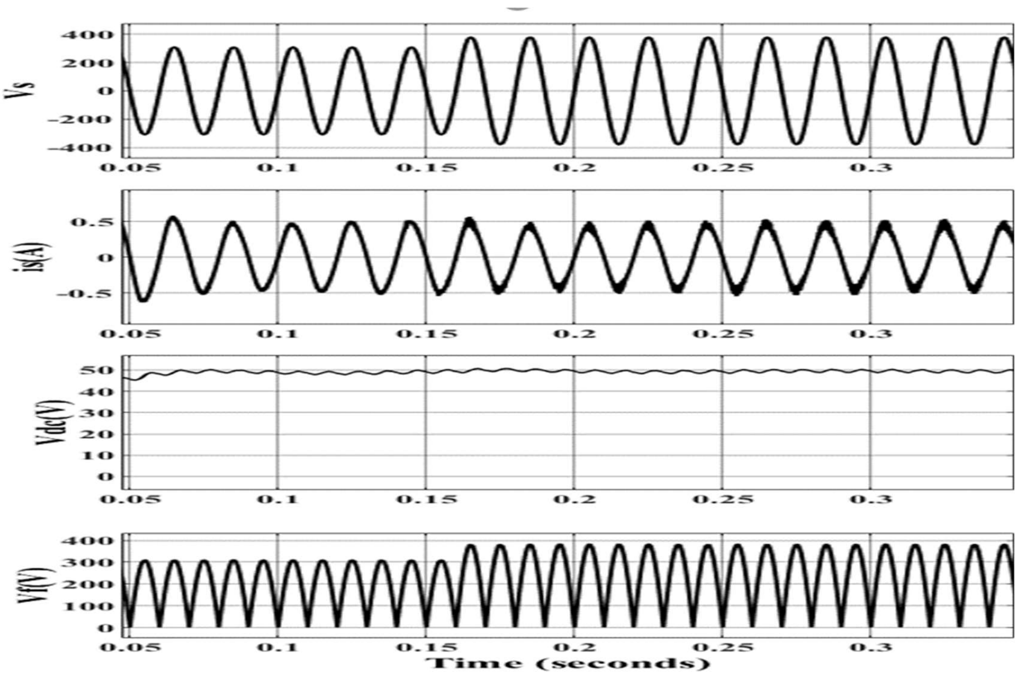

Fig5.7: Input Voltage, Input current, Dc link voltage and capacitor filter voltage at input supply voltage from 220V to 270 V and converter output voltage of 48V

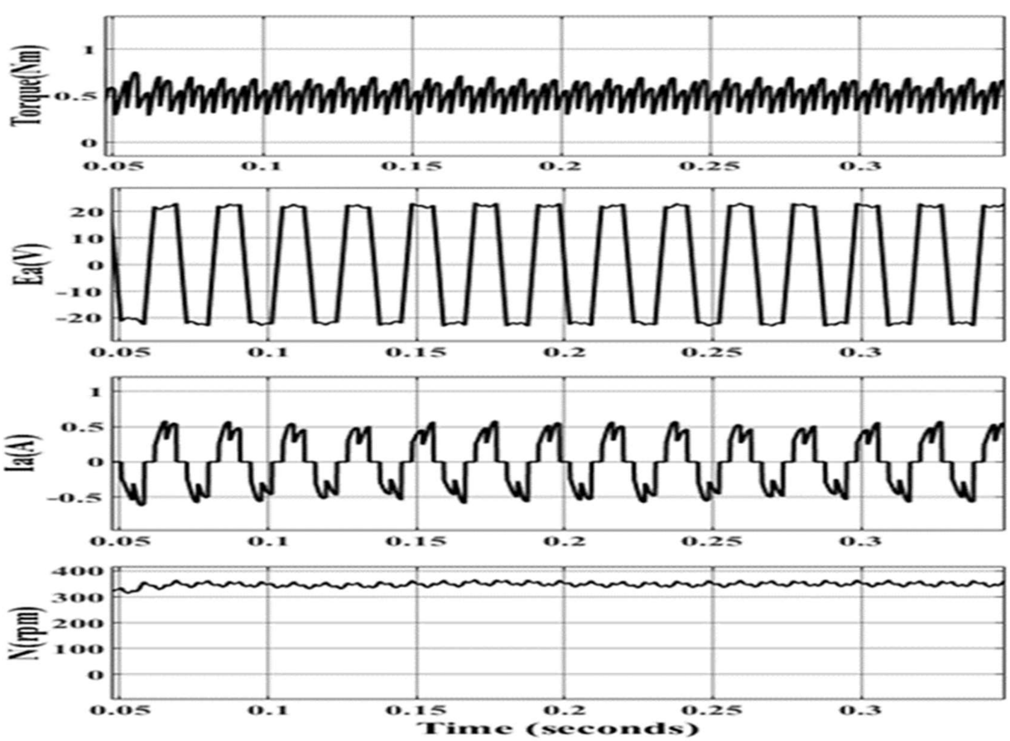

Fig.5.8: performance of ceiling fan under the dynamic condition varies input supply voltage from 220V to 270V at converter output voltage of 48V

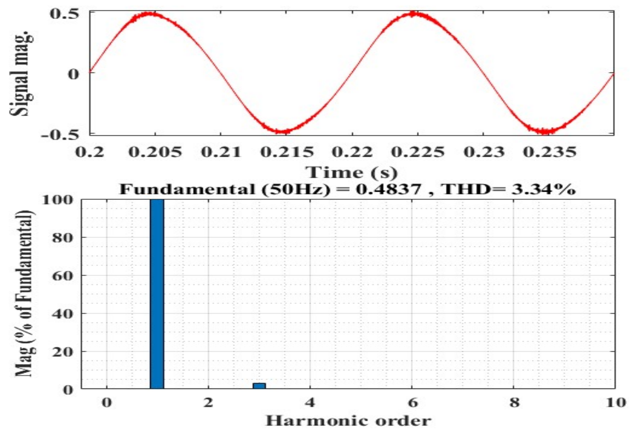

Fig. 5.9: THD in supply current (RMS) at a supply voltage of 270V.

5.8 Summary

The Brush-less DC motor is driven using hall sensors under different voltage conditions and using MATLAB. It is found that the results satisfy the IEC standard 61000-3-2. Table 5.2 and 5.3 shows the performance and power quality of BLDCM ceiling fan under different input supply and different DC voltage respectively. Fig.5.6 and Fig.5.9 shows the THD in input current at 220V and 270V respectively and Fig. 5.3, 5.4, 5.5 shows the steady state operation at 220V and Fig.5.7 and 5.8 shows the dynamic operation from 220V to 270V. Hence BLDC motor fan performs better when there is unstable power supply. This design provides wide range of input and output voltage, very low switching current ripple, small size, high overall conversion efficiency.

Chapter 6

CONCLUSIONS AND FUTURE SCOPE

6.1 Conclusions

The main findings of the study are-

(1) The speed control of BLDC motor can be observed using simulation result.

(2) The difference between trapezoidal method and FOC method can be seen in simulation results which shows the difference between current and torque waveforms.

(3) The steady state and dynamic performance of motor has been studied.

(4) The control strategy in the operation is applied such that it improves the Power factor of the system.

(5) The THD in the input current of the system is very low which satisfy the IEC standard 61000-3-2.

(6) The study shows the performance and power quality of BLDCM ceiling fan under different input supply.

(7) The study also shows the performance and power quality of BLDCM ceiling fan under different DC Voltage.

(8) Hence it is proved that BLDC motor performs better (stable) when there is unstable power supply.

(9) The design provides wide range of input and output voltage, very low switching current ripple, small size, high overall conversion efficiency.

(10) This can be a replacement of induction fans soon.

6.2 Future Scope

In this thesis, we have seen various topologies of converters, the methods used to control the motor and the simulation results of the output of BLDC motor. This can be further extended to

1. The motor can be designed with various different converter topologies.
2. The study of BLDC motor can also be done for EV application as BLDC motors as widely being used in EVs.

LIST OF PUBLICATIONS

[1] T. Agarwal and P. Chittora, "A Complete Overview of Electric Vehicle Along with Battery and PV Interface," 2022 IEEE Delhi Section Conference (DELCON), 2022, pp. 1-7, doi: 10.1109/DELCON54057.2022.9753246. **(Accepted and published)**

[2] T. Agarwal and P. Chittora, "PFC Isolated CUK Converter based Sensored BLDC Motor for the Application of Ceiling Fan", 3rd Electric Power and Renewable Energy Conference (EPREC-2022). **(Accepted)**

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[3] M. Hein “Demystifying BLDC motor commutation: Trap, Sine, & FOC”, https://training.ti.com/demystifying-BLDC-motor-commutation-trap-sine-foc

[4] G. Tatar, K. Toker, N. F. Oyman and H. Korkmaz, "A dynamic analysis of BLDC motor by using Matlab/Simulink and mathematica," 2017 CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON), pp. 1-5, 2017.

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