**THREE PHASE INTELLEGENCE POWER MODULE BASED BRUSHLESS DIRECT CURRENT MOTOR DRIVER**

B.E. ELECTRONIC ENGINEERING, BATCH 2017

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**Internal Advisor**

**Engr. MAQSOOD-UR-REHMAN**

**Lab Engineer**

**SUBMITTED BY**

1.Abdul Rehman D-17 ES-04

2.Samra Arif D-17 ES-18

3.Bisma Naz D-17 ES-20

4.Waqas Ahmed D-17 ES-42

5.Jawad Turabi D-17 ES-76

**DEPARTMENT OF ELECTRONIC ENGINEERING**

**DAWOOD UNIVERSITY OF ENGINEERING AND TECHNOLOGY, KARACHI**

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Report submitted in partial fulfillment of the requirements for the degree

**BACHELOR OF ENGINEERING IN ELECTRONIC ENGINEERING**

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**Department of Electronic Engineering**

Dawood University of Engineering & Technology, Karachi

### CERTIFICATE

**This project “THREE PHASE INTELLEGENCE POWER MODULE BASED BRUSHLESS DIRECT CURRENT MOTOR DRIVER” presented by Abdul Rehman, Samra Arif Bisma Naz, Waqas Ahmed, Jawad Turabi under the direction of their project advisor’s and approved by the project examination committee, has been presented to and accepted as it satisfies the academic requirements in respect of project work prescribed by the Department of Electronic Engineering in partial fulfillment of the requirements for Bachelor of Engineering in Electronic Engineering.**

**ACKNOWLEDGEMENT**

**Abstract**

**CHAPTER 1**

**Overview of the Project**

**I**n this project,we generate three phase of 310Vpp by Intelligent Power Module (IPM) to drive a permanent magnet Brushless Direct Current (BLDC) motor in open loop mode through a microcontroller. We also use internet of things (IOT) to control and monitor the RPM, current, power and other important parameter of BLDC motor of machine.

**INTRODUCTION**

This project provides a technical review of position and speed sensorless methods for controlling Brushless Direct Current (BLDC) motor drives. The performance and reliability of BLDC motor drivers have been improved because the conventional control and sensing techniques have been improved through sensorless technology.The project study includes a deep overview of state-of-the-art back-EMF sensing methods, which includes Terminal Voltage Sensing,

* 1. **PROJECT BACKGROUND**

Due to the their efficiency, silent operation, re alibility and compact form, BLDC motor

have been desired for small horsepower control motors. Nowadays, household appliance is

one of fastest-growing end-product market for electronic motor drive.

Actually, BLDC motor is one type of permanent magnet synchronous motor that can

be driven by dc voltage but current commutation is done by solid state switches. The

commutation instant are determined by the rotor position that will detected by position sensor

or by sensorless technique [1]. These position sensors may be a hall sensors, resolvers or

absolute position sensor. The most type of sensor that normally use is hall sensor and optical

encoders. These sensor especially hall sensors are temperature sensitive and limit.

Therefore, these sensors could reduce the system reliability because of the components

and wiring. Some advantages of BLDC motor compare to brushed DC motor and induction

motor is reliable, long operating life, high efficiency and also high dynamic response [2]. Due

to an advantages of BLDC motor, this project will focused on BLDC machine with trapezoidal

back-EMF and different parameters of speed controller.

2

This simulation will be model by using MATLAB Simulink Software. Simulation is

the most important to evaluate, design and make an analysis of power electronic inverter that

apply such as at BLDC motor. The benefit by using MATLAB software because it provides

immediate access to thousand of fundamental and can be built-in graphing tools and GUI

builder to ensure that can customize data and model to help interpret data more easily for

quicker decision making.

Since 1970s PWM technology was already available and broadly apply because it

offer many advantages such as to minimize lower order harmonic while the higher order

harmonic will be eliminated by using filter. Thus, MATLAB also in affective tool to analyze a

PWM inverter. In this project, the choosen switching device use in inverter will be use is

switch block because it more easy to control. In order to enhance and improve the

performance of electric motor, it can been done by using inverter topologies, control scheme

of the electric drive system and also the motor type that have been choosen to fullfil the

requirement needed.

3

* 1. **PROJECT MOTIVATION**

A brushless DC motor (BLDC) is the most popular of applications for home appliance

and industries such as for medical, aerospace and also can be used in outdoor fan in air conditioner.

It is because their advantage that high efficiency, lower weight, reliability and

also low cost. To control of BLDC motor, an electronic commutation is applied and will make

Power Electronic circuit more complexity. Basically, Voltage Source Inverter (VSI) can be

used to achieve accurate and better performance of BLDC motor. Normally, in designing

motor drive, the suitable designing is by using modeling and simulation compared to building

prototypes because of the cost.

In this project, the simulation of a BLDC motor drive system is developed using

MATLAB/Simulink. All realistic components have been included in the simulation circuit. A

comparative study for hysteresis and PWM control techniques in controller used to fulfill the

requirement during designing the BLDC motor drive. For closed loop operation of the motor

drive, a speed controller also has been designed. The modeling of BLDC motor presents a

switching technique for sensored BLDC motor with Hall Effect sensor with a setting value of

parameters. In the drive block diagram have been designed speed controller for closed loop

operation. The design methods of the PI controller also have given.

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* 1. **PROBLEM STATEMENT**

In many cases, the brushless DC (BLDC) motor can replace conventional DC motor.

BLDC motor are very suitable for air conditioning system application because of their small

size, high reliability, high efficiency and very excellent speed torque characteristics. Induction

machines more difficult to control and achieved torque speed range compare to the BLDC

motor. In term of efficiency, BLDC motor can operate at unity power factor but for induction

machines the best power factor only around 85 percent.

This motor have higher torque ripples compared to the other motor that have a

sinusoidal shaped back EMF. They are also cheaper and very suitable to use for general

application. The type of switching control of Pulse Width Modulation VSI has used to

complete the design. This is because six-step technique inverter normally used widely in the

speed of induction motor that can varies the output frequency. So the suitable technique in this

project is Hysteresis Current Controller VSI because of their characteristic depends on their

excellent dynamic response and easy for implementation. The software will use to analyze this

project is MATLAB Simulink. However, MATLAB software will uses a large amount of

memory in personal computer (PC) and also make the PC running slowly but it offers high

performance numerical computation, data analysis, and application development tools that will

help to finished this project.

5

* 1. **OBJECTIVES**

The main objective in this project is to design and make an analysis of BLDC motor by

using MATLAB Simulink Software. In order to achieve the goal of this project and solve the

current problem, an objective of this project is determined:

1) To analyzed the performance of BLDC motor drive.

2) To investigate the performance of BLDC motor in term of trapezoidal drive via

Matlab/Simulink simulation.

3) To design the PI controller and analyze the performance of BLDC motor using

MATLAB/Simulink

* Universal and configurable hardware moldable on different BLDC’s.
* Smart control according to machine requirement and human interface.
* Power efficient and cost effective
  1. **SCOPE OF RESEARCH**

In producing a successful analysis, work, and some project, the scope is required to

assist and set the directions of the project development. These scope should be identified and

planned appropriately. The main scope is to establish the analysis performance of parameter

for BLDC motor with trapezoidal back-EMF and simulate the controller which is PI controller

with the modelling of the BLDC motor to compare their performance.

6

**1.6 REPORT OUTLINES**

Chapter 1 will fullfill the introduction of three phase inverter for BLDC motor. The overview

of project objectives, problem statement for this project analysis, scope of work and

methadology project which is the method that uses in order to finish this project.

Chapter 2 focuses on the literature review such as theorytical, basic principles and basic

topologies that relates to this project. The research that running is about BLDC motor, inverter

and air conditioner.

Chapter 3 discusses about methadology of this project. The gantt chart and flowchart also

included in this chapter. This chapter also will discuss about circuit design and the system

work. Other than that, in this chapter will discuss about related previous work and will make a

comparison about this.

Chapter 4 will explain the results obtain during construction circuit in Matlab Simulation.

Among the result that will be discussed about output waveform which is sinusoidal and

trapeizoidal waveform that will produce in different input voltage.

Chapter 5 will discuss about the conclusion and the advantages of the method had been

implemented into this project. This chapter also gives the recommendation to improve

software or anything else related to the project.

For the past two decades several Asian countries such as Japan, which have been under pressure from high energy prices, have implemented variable speed PM motor drives for energy saving applications such as air conditioners and refrigerators . On the other hand, the U.S.A. has kept on using cheap induction motor drives, which have around 10% lower efficiency than adjustable PM motor drives for energy saving applications. Therefore recently, the increase in energy prices spurs higher demands of variable speed PM motor drives. Also, recent rapid proliferation of motor drives into the automobile industry, based on hybrid drives, generates a serious demand for high efficient PM motor drives, and this was the beginning of interest in BLDC motors.

**CHAPTER 2**

**LITERATURE REVIEW**

In an open loop control of BLDC, the speed can be controlled only through the control of voltage. These are given as inputs to the base port of the IGBT three phase IPM. Method to detect the rotor position of a 3-phase BLDC motor. Such motors requires three numbers of hall effect sensor for detecting the rotor position[1].

Brushless DC motor drive consist of a DC power supply, an inverter circuit(with solid state switches), driver circuit and a control system [2].

A control system of the BLDC motor proposed through the elimination of the Hall sensors feedback signals and it depends on the motor speed feedback signal only [3].

In modern BLDC drives, self-sensing methods are used to replace the position sensor, the accuracy required in detecting the correct current commutation instants is much higher [4].

**2.1 INTRODUCTION OF DC MOTOR**

In daily life, an electric equipment that we use often to have at least one motor used to

rotate an object from its position. In the market have many type of motor such as induction

motor, servomotors, DC motor (brushed and brushless). To choose the suitable type of motor

depends on the application requirement [3].

**2.1.1 Construction**

Figure 2.1 shows the dc motor that have an armature on the rotor. The stator has salient

magnetic poles that are either made of permanent magnets or special field windings. Current is

fed to the rotor windings through brushes that are in contact with commutator segment lcated

at the end of the rotor. For more understanding, commutator segments also can be known as

copper strips which are connected to the rotor windings [4].

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Figure 2.1: Cross section of a two pole dc motor

As the rotor states, the brushes move from one segment to another which commutates

the current in such a way that the currents in the conductor under each pole flow in the same

direction which is from stator point of view have been depicted in Figure 2.2. The resulting

force vectors that act on the rotor windings are all tangetial to the rotor periphery and

contribute to the torque.

Figure 2.2: Brush and commutator segment of dc motor

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**2.2 BRUSHLESS DC (BLDC) MOTOR**

**2.2.1 Introduction**

Brushless DC motors also can be known as electronically commutated motors that are

powered by direct-current (DC) electricity and having electronic commutation systems rather

than mechanical commutator and brushes [5]. BLDC motor having permanent magnets on the

rotor and trapeizoidal shape back-EMF. BLDC motor also one kind of permanent magnet

synchrous motor. The Brushless Direct Current (BLDC) motor used in a medical application,

industries and also used in aerospace and defense application for recent years. It very ideal for

application that require high reliability, high efficiency and high performance motor because it

capable to providing large amount of torque over a vast speed range.

The application that suitable for BLDC motor such single-speed applications,

adjustable speed, position control, and in low-noise application. In term of single speed,

BLDC are good for this application because of the flat speed torque curve when speed has to

be maintained in the variation of load. To monitor torque, speed and position control for

BLDC motors a complex controllers and optical encoder can use for it. The BLDC motors also

generate EMI and noise but its better compare to Brushed DC motor [2].

Other than that, the household appliance such as room conditioner, refrigerator, water

heaters and medical application also use BLDC motor for example of medical application such

as Sleep Apnea Treatment because the higher heat will transfer efficient to allow them to run

cooler in crowded spaces.

or the past two decades several Asian countries such as Japan, which have been under pressure from high energy prices, have implemented variable speed PM motor drives for energy saving applications such as air conditioners and refrigerators [[1](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b1-sensors-10-06901)]. On the other hand, the U.S.A. has kept on using cheap induction motor drives, which have around 10% lower efficiency than adjustable PM motor drives for energy saving applications. Therefore recently, the increase in energy prices spurs higher demands of variable speed PM motor drives. Also, recent rapid proliferation of motor drives into the automobile industry, based on hybrid drives, generates a serious demand for high efficient PM motor drives, and this was the beginning of interest in BLDC motors.

BLDC motors, also called Permanent Magnet DC Synchronous motors, are one of the motor types that have more rapidly gained popularity, mainly because of their better characteristics and performance [[2](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b2-sensors-10-06901)]. These motors are used in a great amount of industrial sectors because their architecture is suitable for any safety critical applications.

The brushless DC motor is a synchronous electric motor that, from a modelling perspective, looks exactly like a DC motor, having a linear relationship between current and torque, voltage and rpm. It is an electronically controlled commutation system, instead of having a mechanical commutation, which is typical of brushed motors. Additionally, the electromagnets do not move, the permanent magnets rotate and the armature remains static. This gets around the problem of how to transfer current to a moving armature. In order to do this, the brush-system/commutator assembly is replaced by an intelligent electronic controller, which performs the same power distribution as a brushed DC motor [[3](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b3-sensors-10-06901)]. BLDC motors have many advantages over brushed DC motors and induction motors, such as a better speed *versus* torque characteristics, high dynamic response, high efficiency and reliability, long operating life (no brush erosion), noiseless operation, higher speed ranges, and reduction of electromagnetic interference (EMI). In addition, the ratio of delivered torque to the size of the motor is higher, making it useful in applications where space and weight are critical factors, especially in aerospace applications.

The control of BLDC motors can be done in sensor or sensorless mode, but to reduce overall cost of actuating devices, sensorless control techniques are normally used. The advantage of sensorless BLDC motor control is that the sensing part can be omitted, and thus overall costs can be considerably reduced. The disadvantages of sensorless control are higher requirements for control algorithms and more complicated electronics [[3](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b3-sensors-10-06901)]. All of the electrical motors that do not require an electrical connection (made with brushes) between stationary and rotating parts can be considered as brushless permanent magnet (PM) machines [[4](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b4-sensors-10-06901)], which can be categorised based on the PMs mounting and the back-EMF shape. The PMs can be *surface mounted on the rotor* (SMPM) or installed *inside of the rotor* (IPM) [[5](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b5-sensors-10-06901)], and the back-EMF shape can either be sinusoidal or trapezoidal. According to the back-EMF shape, *PM AC synchronous motors* (PMAC or PMSM) have sinusoidal back-EMF and *Brushless DC motors* (BLDC or BPM) have trapezoidal back-EMF. A PMAC motor is typically excited by a three-phase sinusoidal current, and a BLDC motor is usually powered by a set of currents having a quasi-square waveform [[6](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b6-sensors-10-06901),[7](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b7-sensors-10-06901)].

Because of their high power density, reliability, efficiency, maintenance free nature and silent operation, permanent magnet (PM) motors have been widely used in a variety of applications in industrial automation, computers, aerospace, military (gun turrets drives for combat vehicles) [[3](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b3-sensors-10-06901)], automotive (hybrid vehicles) [[8](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b8-sensors-10-06901)] and household products. However, the PM BLDC motors are inherently electronically controlled and require rotor position information for proper commutation of currents in its stator windings. It is not desirable to use the *position sensors* for applications where reliability is of utmost importance because a sensor failure may cause instability in the control system. These limitations of using position sensors combined with the availability of powerful and economical microprocessors have spurred the development of sensorless control technology. Solving this problem effectively will open the way for full penetration of this motor drive into all low cost, high reliability, and large volume applications.

The remainder of the paper is arranged as follows. Section 2 describes the position and speed control fundamentals of BLDC motors using sensors. Next, Section 3 explains the control improvements applying sensorless techniques, describing the motor controller model and the most important techniques based on back-EMF sensing. Section 4 also briefly analyses the sensorless techniques using estimators and model-based schemes. In addition, Section 5 compares the feasibility of the control methods, and describes some relevant implementation issues, such as open-loop starting. Finally, Section 6 provides an overview for the applications of BLDC motor controllers, as well as conclusions are drawn in Section 7.

2. **Position and Speed Control of BLDC Motors Using Sensors**

PM motor drives require a rotor position sensor to properly perform phase commutation and/or current control. For PMAC motors, a constant supply of position information is necessary; thus a position sensor with high resolution, such as a *shaft encoder or a resolver*, is typically used. For BLDC motors, only the knowledge of six phase-commutation instants per electrical cycle is needed; therefore, low-cost *Hall-effect sensors* are usually used. Also, *electromagnetic variable reluctance* (VR) *sensors* or *accelerometers* have been extensively applied to measure motor position and speed. The reality is that angular motion sensors based on magnetic field sensing principles stand out because of their many inherent advantages and sensing benefits.

**2.1. Position and Speed Sensors**

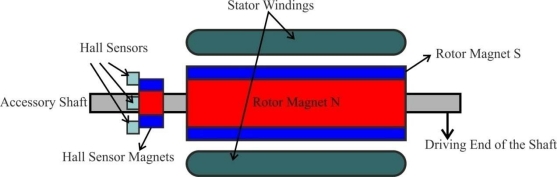
As explained before, some of the most frequently used devices in position and speed applications are Hall-effect sensors, variable reluctance sensors and accelerometers. Each of these types of devices is discussed further below.

**2.1.1. Hall-effect sensors**

These kinds of devices are based on Hall-effect theory, which states that if an electric current- carrying conductor is kept in a magnetic field, the magnetic field exerts a transverse force on the moving charge carriers that tends to push them to one side of the conductor. A build-up of charge at the sides of the conductors will balance this magnetic influence producing a measurable voltage between the two sides of the conductor. The presence of this measurable transverse voltage is called the Hall-effect because it was discovered by Edwin Hall in 1879.

Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall-effect sensors embedded into the stator [[9](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b9-sensors-10-06901)].

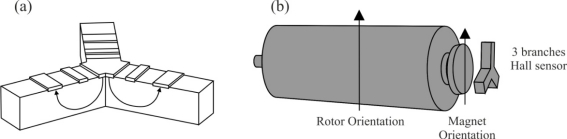
Most BLDC motors have three Hall sensors inside the stator on the non-driving end of the motor. Whenever the rotor magnetic poles pass near the Hall sensors they give a high or low signal indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined. [Figure 1](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f1-sensors-10-06901/) shows a transverse section of a BLDC motor with a rotor that has alternate N and S permanent magnets. Hall sensors are embedded into the stationary part of the motor. Embedding the Hall sensors into the stator is a complex process because any misalignment in these Hall sensors with respect to the rotor magnets will generate an error in determination of the rotor position. To simplify the process of mounting the Hall sensors onto the stator some motors may have the Hall sensor magnets on the rotor, in addition to the main rotor magnets. Therefore, whenever the rotor rotates the Hall sensor magnets give the same effect as the main magnets. The Hall sensors are normally mounted on a printed circuit board and fixed to the enclosure cap on the non-driving end. This enables users to adjust the complete assembly of Hall sensors to align with the rotor magnets in order to achieve the best performance [[10](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b10-sensors-10-06901)].

[[](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f1.jpg)](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f1.jpg" \t "tileshopwindow)

[Figure 1.](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f1-sensors-10-06901/)

BLDC motor transverse section [[10](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b10-sensors-10-06901)].

Nowadays, because miniaturized brushless motors are introduced in many applications, new position sensors are being developed, such as a three branches vertical Hall sensor [[11](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b11-sensors-10-06901)] depicted in [Figure 2a](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f2-sensors-10-06901/). The connecting principle between the brushless motor and this sensor is reminiscent of the miniaturized magnetic angular encoder based on 3-D Hall sensors. A permanent magnet is fixed at the end of a rotary shaft and the magnetic sensor is placed below, and the magnet creates a magnetic field parallel to the sensor surface. This surface corresponds to the sensitive directions of the magnetic sensor. Three-phase brushless motors need three signals with a phase shift of 120° for control, so a closed-loop regulation may be used to improve the motor performance. Each branch could be interpreted as a half of a vertical Hall sensor and are rotated by 120° in comparison to the other. Only a half of a vertical Hall sensor is used since little space is available for the five electrical contacts (two for the supply voltage and three to extract the Hall voltages). This sensor automatically creates three signals with a phase shift of 120°, which directly correspond to the motor driving signals, to simplify the motor control in a closed-loop configuration. A drawing of this device’s use as angular position sensor for brushless motor control is given in [Figure 2b](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f2-sensors-10-06901/). A first alignment is between the rotor orientation and the permanent magnet, and a second alignment is between the stator and the sensor. This alignment will allow the motion information for the motor and the information about its shaft angular position.

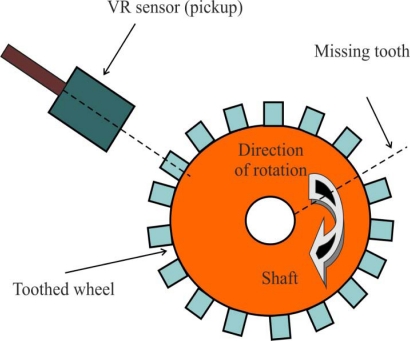
[[](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f2.jpg)](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f2.jpg" \t "tileshopwindow)

[Figure 2.](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f2-sensors-10-06901/)

**(a)** Schematic representation of a three branches Hall sensor. **(b)** Three branches vertical Hall device mounted as angular position sensor for brushless motor control [[11](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b11-sensors-10-06901)].

**2.1.2. Variable reluctance (VR) wheel speed sensors**

This kind of sensor is used to measure position and speed of moving metal components, and is often referred as a passive magnetic sensor because it does not need to be powered. It consist of a permanent magnet, a ferromagnetic pole piece, a pickup coil, and a rotating toothed wheel, as [Figure 3](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f3-sensors-10-06901/) illustrates. This device is basically a permanent magnet with wire wrapped around it. It is usually a simple circuit of only two wires where in most cases polarity is not important, and the physics behind its operation include magnetic induction [[12](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b12-sensors-10-06901)].

[[](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f3.jpg)](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f3.jpg" \t "tileshopwindow)

[Figure 3.](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f3-sensors-10-06901/)

Variable Reluctance sensor that senses movement of the toothed wheel [[12](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b12-sensors-10-06901)].

As the teeth pass through the sensor’s magnetic field, the amount of magnetic flux passing through the permanent magnet varies. When the tooth gear is close to the sensor, the flux is at maximum. When the tooth is further away, the flux drops off. The moving target results in a time-varying flux that induces a voltage in the coil, producing an electrical analog wave. *The frequency and voltage of the analog signal is proportional to velocity of the rotating toothed wheel.* Each passing discontinuity in the target causes the VR sensor to generate a pulse. The cyclical pulse train or a digital waveform created can be interpreted by the BLDC motor controller.

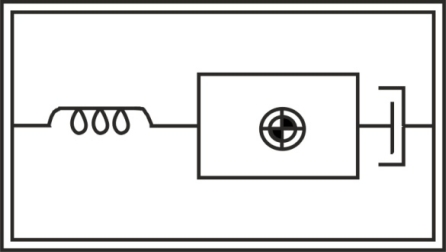
The advantages of the VR sensor can be summarized as follows: low cost, robust proven speed and position sensing technology (it can operate at temperatures in excess of 300 °C), self-generating electrical signal which requires no external power supply, fewer wiring connections which contribute to excellent reliability, and a wide range of output, resistance, and inductance requirements so that the device can be tailored to meet specific control requirements [[12](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b12-sensors-10-06901)].

Due to the fact that these sensors are very small, they can be embedded in places where other sensors may not fit. For instance, when sealed in protective cases they can be resistant to high temperatures and high pressures, as well as chemical attacks [[13](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b13-sensors-10-06901)]. Through the monitoring of the health of running motors, severe and unexpected motor failures can be avoided and control system reliability and maintainability can be improved. If the VR was integrated inside a motor case for an application in a harsh environment, sensor cables could be easily damaged in that environment. Then, a wireless and powerless sensing solution should be applied using electromagnetic pulses for passing through the motor casing to deliver the sensor signal to the motor controller [[14](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b14-sensors-10-06901)].

The *Hall-effect sensor* explained before is an alternative but more expensive technology, so *VR sensors* are the most suitable choice to measure the rotor position and speed.

**2.1.3. Accelerometers**

An accelerometer is a electromechanical device that measures acceleration forces, which are related to the freefall effect. Several types are available to detect magnitude and direction of the acceleration as a vector quantity, and can be used to sense position, vibration and shock. The most common design is based on a combination of Newton’s law of mass acceleration and Hooke’s law of spring action [[13](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b13-sensors-10-06901)]. Then, conceptually, an accelerometer behaves as a damped mass on a spring, which is depicted in [Figure 4](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f4-sensors-10-06901/). When the accelerometer experiences acceleration, the mass is displaced to the point that the spring is able to accelerate the mass at the same rate as the casing. The displacement is then measured to give the acceleration.

[[](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f4.jpg)](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f4.jpg" \t "tileshopwindow)

[Figure 4.](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f4-sensors-10-06901/)

Basic spring-mass system accelerometer [[13](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b13-sensors-10-06901)].

Under steady-state conditions, the measurement of acceleration is reduced to a measurement of spring extension (linear displacement) showed in [Equation (1)](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#FD1):

a=km · Δx

(1)

where *k* is the spring constant, *m* is the seismic (or proof) mass, and *Δx* is the distance that is stretched the spring from its equilibrium position with a force given by [Equation (2)](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#FD2), which is described by Newton’s and Hooke’s laws:

*F* = *k*  ·  Δ*x*

(2)

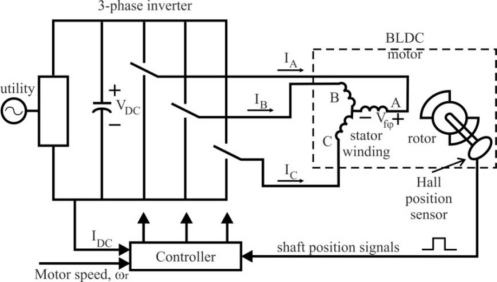
There is a wide variety of accelerometers depending on the requirements of natural frequency, damping, temperature, size, weight, hysteresis, and so on. Some of these types are piezoelectric, piezoresistive, variable capacitance, linear variable differential transformers (LVDT), potentiometric, among many others [[13](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b13-sensors-10-06901)].

Modern accelerometers are often small micro electro-mechanical systems (MEMS), and are indeed the simplest MEMS devices possible, and consist of little more than a cantilever beam with a proof mass. The MEMS accelerometer is silicon micro-machined, and therefore, can be easily integrated with the signal processing circuits [[14](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b14-sensors-10-06901)]. This is different when compare with a traditional accelerometer such as the piezoelectric kind.

**2.2. Conventional Control Method Using Sensors**

A BLDC motor is driven by voltage strokes coupled with the rotor position. These strokes must be properly applied to the active phases of the three-phase winding system so that the angle between the stator flux and the rotor flux is kept close to 90° to get the maximum generated torque. Therefore, the controller needs some means of determining the rotor's orientation/position (relative to the stator coils), such as Hall-effect sensors, which are mounted in or near the machine’s air gap to detect the magnetic field of the passing rotor magnets. Each sensor outputs a high level for 180° of an electrical rotation, and a low level for the other 180°. The three sensors have a 60° relative offset from each other. This divides a rotation into six phases (3-bit code) [[9](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b9-sensors-10-06901)].

The process of switching the current to flow through only two phases for every 60 electrical degree rotation of the rotor is called *electronic commutation*. The motor is supplied from a three-phase inverter, and the switching actions can be simply triggered by the use of signals from position sensors that are mounted at appropriate points around the stator. When mounted at 60 electrical degree intervals and aligned properly with the stator phase windings these Hall switches deliver digital pulses that can be decoded into the desired three-phase switching sequence [[15](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b15-sensors-10-06901)]. A BLDC motor drive with a six-step inverter and Hall position sensors is shown in [Figure 5](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f5-sensors-10-06901/).

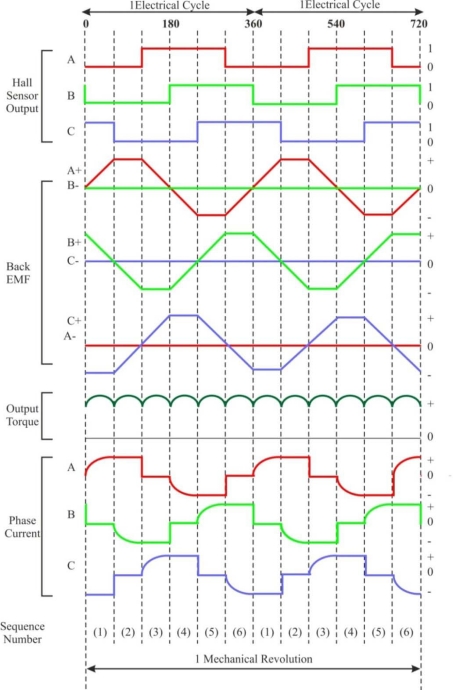
[[](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f5.jpg)](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f5.jpg" \t "tileshopwindow)

[Figure 5.](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f5-sensors-10-06901/)

Electronically commutated BLDC motor drive [[16](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b16-sensors-10-06901)].

Such a drive usually also has a current loop to regulate the stator current, and an outer speed loop for speed control [[16](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b16-sensors-10-06901)]. The speed of the motor can be controlled if the voltage across the motor is changed, which can be achieved easily varying the duty cycle of the PWM signal used to control the six switches of the three-phase bridge.

Only two inverter switches, one in the upper inverter bank and one in the lower inverter bank, are conducting at any instant. These discrete switching events ensure that the sequence of conducting pairs of stator terminals is maintained [[16](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b16-sensors-10-06901)]. [Figure 6](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f6-sensors-10-06901/) shows an example of Hall sensor signals with respect to back-EMF and the phase current. One of the Hall sensors changes the state every 60 electrical degrees of rotation. Given this, it takes six steps to complete an electrical cycle. However, one electrical cycle may not correspond to a complete mechanical revolution of the rotor. The number of electrical cycles to be repeated to complete a mechanical rotation is determined by the rotor pole pairs. For each rotor pole pair, one electrical cycle is completed. *The number of electrical cycles/rotations equals the rotor pole pairs* [[10](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b10-sensors-10-06901)]. This sequence of conducting pairs is essential to the production of a constant output torque.

[[](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f6.jpg)](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f6.jpg" \t "tileshopwindow)

[Open in a separate window](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f6-sensors-10-06901/?report=objectonly)

[Figure 6.](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f6-sensors-10-06901/)

Hall sensor signal, back-EMF, output torque and phase current [[10](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b10-sensors-10-06901)].

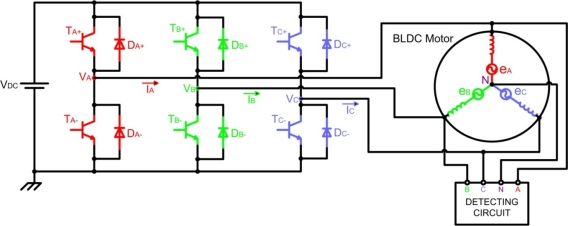
In summary, permanent magnet motor drives require a rotor position sensor to properly perform phase commutation, but there are several drawbacks when such types of position sensors are used. The main drawbacks are the increased cost and size of the motor, and a special arrangement needs to be made for mounting the sensors. Further, Hall sensors are temperature sensitive and hence the operation of the motor is limited, which could reduce the system reliability because of the extra components and wiring [[7](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b7-sensors-10-06901)]. To reduce cost and improve reliability such position sensors may be eliminated. To this end, many sensorless schemes have been reported for position (and speed) control of BLDC motors [[6](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b6-sensors-10-06901)].

**Techniques and Advances in Sensorless Control**

Position sensors can be completely eliminated, thus reducing further cost and size of motor assembly, in those applications in which only variable speed control (*i.e.*, no positioning) is required and system dynamics is not particularly demanding (*i.e.*, slowly or, at least, predictably varying load). In fact, some control methods, such as back-EMF and current sensing, provide, in most cases, enough information to estimate with sufficient precision the rotor position and, therefore, to operate the motor with synchronous phase currents. A PM brushless drive that does not require position sensors but only electrical measurements is called a *sensorless drive* [[4](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b4-sensors-10-06901)].

The BLDC motor provides an attractive candidate for sensorless operation because the nature of its excitation inherently offers a low-cost way to extract rotor position information from motor-terminal voltages. In the excitation of a three-phase BLDC motor, except for the phase-commutation periods, only two of the three phase windings are conducting at a time and the no conducting phase carries the back-EMF. There are many categories of sensorless control strategies [[6](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b6-sensors-10-06901)]; however, the most popular category is based on back electromotive forces or back-EMFs [[17](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b17-sensors-10-06901)]. Sensing back-EMF of unused phase is the most cost efficient method to obtain the commutation sequence in star wound motors. Since back-EMF is zero at standstill and proportional to speed, the measured terminal voltage that has large signal-to-noise ratio cannot detect zero crossing at low speeds. That is the reason why in all back-EMF-based sensorless methods the low-speed performance is limited, and an *open-loop starting strategy* is required [[18](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b18-sensors-10-06901)].

Generally, a brushless DC motor consists of a permanent magnet synchronous motor that converts electrical energy to mechanical energy, an inverter corresponding to brushes and commutators, and a *shaft position sensor* [[19](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b19-sensors-10-06901)], as [Figure 7](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f7-sensors-10-06901/) shows. In this figure, each of the three inverter phases are highlighted in a different colour, including the neutral point: red phase *A*, green phase *B*, blue phase *C*, and pink neutral point *N*. The stator iron of the BLDC motor has a non-linear magnetic saturation characteristic, which is the basis from which it is possible to determine the initial position of the rotor. When the stator winding is energized, applying a DC voltage for a certain time, a magnetic field with a fixed direction will be established. Then, the current responses are different due to the inductance difference, and this variation of the current responses contains the information of the rotor position [[20](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b20-sensors-10-06901)]. Therefore, *the inductance of stator winding is a function of the rotor position*.

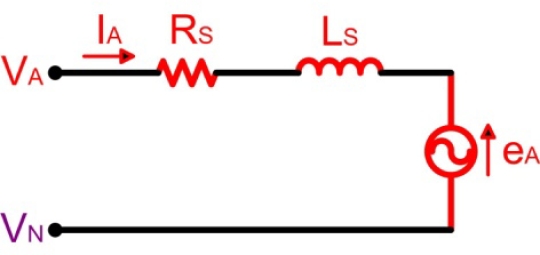
[[](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f7.jpg)](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f7.jpg" \t "tileshopwindow)

[Figure 7.](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f7-sensors-10-06901/)

Typical sensorless BLDC motor drive [[19](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b19-sensors-10-06901)].

The analysis of the circuit depicted in [Figure 7](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f7-sensors-10-06901/) is based on the motor model for phase *A* (highlighted in red colour), illustrated in [Figure 8](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f8-sensors-10-06901/), and the following assumptions are considered [[21](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b21-sensors-10-06901)]:

* The motor is not saturated.
* Stator resistances of all the windings are equal (*RS*), self inductances are constant (*LS*) and mutual inductances (*M*) are zero.
* Iron losses are negligible.

[[](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f8.jpg)](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f8.jpg" \t "tileshopwindow)

[Figure 8.](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f8-sensors-10-06901/)

Equivalent circuit of the BLDC motor for phase *A* [[21](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b21-sensors-10-06901)].

Then, the voltage function of the conducting phase winding might be expressed as indicated in [Equation (3)](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#FD3):

VDC=I · RS+LS · dIdt+e

(3)

where *VDC* is the DC-link voltage, *RS* and *LS* are the equivalent resistance and inductance of stator phase winding respectively, and *e* is the trapezoidal shaped back-EMF.

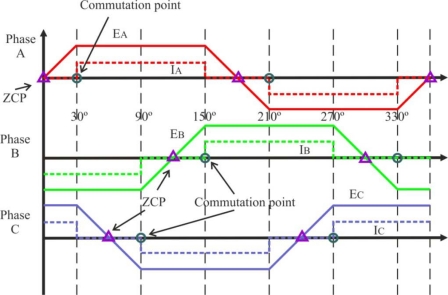
In this paper, conventional and recent advancement of back-EMF sensing methods for the PM BLDC motors and generators are presented, which are split in two categories; direct and indirect back-EMF detection [[22](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b22-sensors-10-06901)]:

* *Direct back-EMF detection methods*: the back-EMF of floating phase is sensed and its zero crossing is detected by comparing it with neutral point voltage. This scheme suffers from high common mode voltage and high frequency noise due to the PWM drive, so it requires low pass filters, and voltage dividers. The methods can be classified as:
  + ○ Back-EMF Zero Crossing Detection (ZCD) or Terminal Voltage Sensing.
  + ○ PWM strategies.
* *Indirect back-EMF detection methods*: because filtering introduces commutation delay at high speeds and attenuation causes reduction in signal sensitivity at low speeds, the speed range is narrowed in direct back-EMF detection methods. In order to reduce switching noise, the indirect back-EMF detection methods are used. These methods are the following:
  + ○ Back-EMF Integration.
  + ○ Third Harmonic Voltage Integration.
  + ○ Free-wheeling Diode Conduction or Terminal Current Sensing.

**Back-EMF Zero Crossing Detection method (Terminal Voltage Sensing)**

The zero-crossing approach is one of the simplest methods of back-EMF sensing technique, and is based on detecting the instant at which the back-EMF in the unexcited phase crosses zero. This zero crossing triggers a timer, which may be as simple as an RC time constant, so that the next sequential inverter commutation occurs at the end to this timing interval [[23](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b23-sensors-10-06901)].

For typical operation of a BLDC motor, the phase current and back-EMF should be aligned to generate constant torque. The current commutation point shown in [Figure 9](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f9-sensors-10-06901/) can be estimated by the zero crossing point (ZCP) of back-EMFs and a 30° phase shift [[1](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b1-sensors-10-06901),[4](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b4-sensors-10-06901)], using a six-step commutation scheme through a three-phase inverter for driving the BLDC motor. The conducting interval for each phase is 120 electrical degrees. Therefore, only two phases conduct current at any time, leaving **the** third phase floating. In order to produce maximum torque, the inverter should be commutated every 60° by detecting zero crossing of back-EMF on the floating coil of the motor [[24](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b24-sensors-10-06901)], so that current is in phase with the back-EMF.

[[](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f9.jpg)](https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=3231115_sensors-10-06901f9.jpg" \t "tileshopwindow)

[Figure 9.](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f9-sensors-10-06901/)

Zero crossing points of the back-EMF and phase current commutation points [[25](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b25-sensors-10-06901)].

This technique of delaying 30° (electrical degrees) from zero crossing instant of the back-EMF is not affected much by speed changes [[7](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b7-sensors-10-06901)]. To detect the ZCPs, the phase back-EMF should be monitored during the silent phase (when the particular phase current is zero) and the terminal voltages should be low-pass filtered first.

Three low-pass filters (LPFs) are utilized to eliminate higher harmonics in the phase terminal voltages caused by the inverter switching. The time delay of LPFs will limit the high speed operation capability of the BLDC machine [[1](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b1-sensors-10-06901),[24](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b24-sensors-10-06901),[26](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b26-sensors-10-06901)]. It’s necessary to point out the importance of filters when a BLDC motor drive is designed, which are used to eliminate high frequency components of the terminal voltages and to extract back-EMF of the motor.

The terminal voltage of the opened or floating phase is given by [Equation (4)](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#FD4):

VC=eC+VN=eC+VCE−VF2−eA+eB2

(4)

where *eC* is the back-EMF of the opened phase (*C*), *VN* is the potential of the motor neutral point, and *VCE* and *VF* are the forward voltage drop of the transistors and diodes, respectively, which implement the motor inverter of [Figure 7](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f7-sensors-10-06901/), respectively.

As the back-EMF of the two conducting phases (A and B) have the same amplitude but opposite sign [[19](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b19-sensors-10-06901)] the terminal voltage of the floating phase results in [Equation (5)](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#FD5):

eA=−eB⇒VC=eC+VCE−VF2=eC+VB+VA2

(5)

where *VA=*−*VF* (forward current of diode *DA*−) and *VB=VCE* (collector-emitter voltage of transistor *TB*−)

Since the zero-crossing point detection is done at the end of the PWM on-state and only the high-side of the inverter is chopped, and *VCE* is similar to *TA*+ and *TB*− transistors, the final detection formula can be represented by [Equation (6)](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#FD6):

VCEA+≈VCEB−⇒VC=eC+VCEB−+VDC−VCEA+2≈eC+VDC2

(6)

Therefore, *the zero-crossing occurs when the voltage of the floating phase reaches one half of the DC rail voltage*. The reason why the end of the PWM on-state is selected as the zero-crossing detection point is that it is noise free to sample at that moment [[20](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b20-sensors-10-06901)].

On the other hand, instead of using analogue LPFs, a unipolar pulse width modulation (PWM) scheme can be used to measure terminal voltages [[27](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b27-sensors-10-06901),[28](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b28-sensors-10-06901)]. The difference of the ZCD method between on and off state of the PWM signal can also be taken into account [[29](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b29-sensors-10-06901),[30](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b30-sensors-10-06901)]. Also, the true phase back-EMF signal could be directly obtained from the motor terminal voltage by properly choosing the PWM and sensing strategy (without the motor neutral point voltage information This would provide advantages such as no sensitivity to switching noise, no filtering required, and good motor performance a wide speed range [[24](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b24-sensors-10-06901),[31](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b31-sensors-10-06901)].

The price for the simplicity of the zero-crossing method tends to be noise sensitivity in detecting the zero crossing, and degraded performance over wide speed ranges unless the timing interval is programmed as a function of rotor speed [[23](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b23-sensors-10-06901)]. Another drawback is that it is not possible to use the noisy terminal voltage to obtain a switching pattern at low speeds since back-EMF is zero at standstill and proportional to rotor speed. Also, the estimated commutation points have position error during the transient period when the speed is accelerated or decelerated rapidly, especially for a system that has low inertia. With this method, rotor position can be detected typically from 20% of the rated speed, then a reduced speed operating range is normally used, typically around 1,000–6,000 rpm [[1](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b1-sensors-10-06901)].

**Optimizations**

As the rotor position information can be extracted by indirectly sensing the back-EMF from only one of the three motor-terminal voltages for a three-phase motor, it is obvious that sensing each terminal voltage can provide two commutation instants. Measuring the time between these two instants, it is possible to interpolate the other four commutation instants ([Figure 9](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f9-sensors-10-06901/) shows that six commutation points are needed), assuming motor speed does not change significantly over consecutive electrical cycles. Depending on the terminal voltage sensing locations, either a low-pass filter or a band-pass filter is used for position information retrieval. The circuit for sensing the other two terminal voltages can therefore be eliminated, leading to a significant reduction in the component count of the sensing circuit. Also, the ZCD method could be improved if a digital filtering procedure is used to identify the true and false ZCPs of phase back-EMF, which are caused by the terminal voltage spikes due to phase commutations [[32](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b32-sensors-10-06901)].

An indirect way of detecting the ZCP of the back-EMF from the three terminal voltages without using the neutral potential is using the difference of the line voltages [[33](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b33-sensors-10-06901)]. Another modification of the technique is to achieve the sensorless commutation by means of a Phase Locked Loop (PLL) and sensing of the phase winding back-EMF voltages [[8](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b8-sensors-10-06901)]. This PLL has a narrow speed range due to the capabilities of the phase detector, and is sensitive to switching noise. In order to simplify the BLDC driver design, it can be built around a sensorless controller chip ML4425 from Fairchild Semiconductor [[34](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b34-sensors-10-06901),[35](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b35-sensors-10-06901)].

A sensorless Field Oriented Control (FOC) of brushless motors [[36](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b36-sensors-10-06901)], which is known to be more efficient in terms of torque generation compared to back-EMF zero crossing detection methods, is currently under development, and it could be successfully applied to the design of motor pump units for automotive applications [[4](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b4-sensors-10-06901)].

At low speeds or at standstill, the back-EMF detection method can not be applied well because the back-EMF is proportional to the motor speed. In spite of this problem, a starting procedure can be used to start the motor from standstill [[20](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b20-sensors-10-06901)]. In critical applications, such as the intelligent Electro-Mechanical (EMA) and Electro-Hydraulic (EHA) actuators of aviation systems, it is necessary to ensure correct start-up of the DC motor. Electrical commutation in the first running stage is normally realized by classical PWM signal that drives a transistor power stage (see [Figure 7](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/figure/f7-sensors-10-06901/)), which is *open-loop control* without any position feedback [[3](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b3-sensors-10-06901)].

At high speeds, the long settling time of a parasitic resonant between the motor inductance and the parasitic capacitance of power devices can cause false zero crossing detection of back-EMF. The solution to this problem is to *detect the back-EMF during on time* at high duty cycle [[37](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b37-sensors-10-06901)], so there is enough time for the resonant transient to settle down. Then, during motor start-up and low speed, it is preferred to use the original scheme since there is no signal attenuation; while at high speed, the system can be switched to the improved back-EMF sensing scheme. With the combination of two detection schemes in one system, the motor can run very well over a *wide speed range* [[24](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b24-sensors-10-06901),[38](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b38-sensors-10-06901)].

**Applications**

The terminal voltage sensing method is widely used for low cost industrial applications such as fans, pumps and compressor drives where frequent speed variation is not required. Nevertheless, BLDC motors need a *rotor position sensor*, and this reduces the system ruggedness, complicates the motor configuration and its mass production. This sensor can be has been eliminated through this sensing technique. In spite of the back-EMF being zero at standstill, this technique permits the starting of a separately controlled synchronous motor without a sensor, because the PWM signal generated in the control computer chops the motor voltage by the commutation transistors to control the motor speed [[1](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b1-sensors-10-06901)]. An example is a motor pump unit, developed for commercial vehicle applications, in which control strategy can be based on the back-EMF zero-crossing method, and speed control loop is closed by means of the virtual feedback provided by the commutation point prediction [[4](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b4-sensors-10-06901)].

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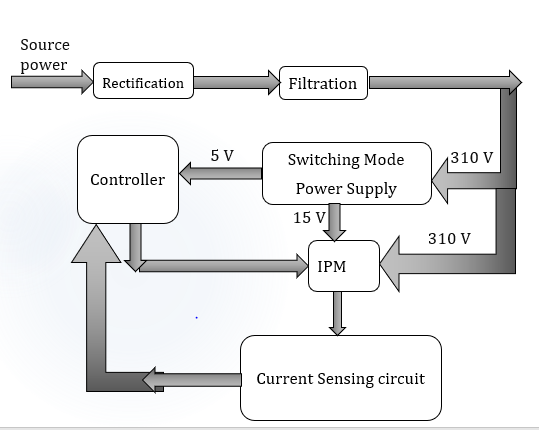
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**CHAPTER THREE:**

**BLOCK DIAGRAM**

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**Chapter four:**

**Brushless Direct Current (BLDC) motor**

BLDC motors, also called Permanent Magnet DC Synchronous motors, are one of the motor types that have more rapidly gained popularity, mainly because of their better characteristics and performance . These motors are used in a great amount of industrial sectors because their architecture is suitable for any safety critical applications.

The brushless DC motor is a synchronous electric motor that, from a modelling perspective, looks exactly like a DC motor, having a linear relationship between current and torque, voltage and rpm. It is an electronically controlled commutation system, instead of having a mechanical commutation, which is typical of brushed motors. Additionally, the electromagnets do not move, the permanent magnets rotate and the armature remains static. This gets around the problem of how to transfer current to a moving armature. In order to do this, the brush-system/commutator assembly is replaced by an intelligent electronic controller, which performs the same power distribution as a brushed DC motor. BLDC motors have many advantages over brushed DC motors and induction motors, such as a better speed versus torque characteristics, high dynamic response, high efficiency and reliability, long operating life (no brush erosion), noiseless operation, higher speed ranges, and reduction of electromagnetic interference (EMI). In addition, the ratio of delivered torque to the size of the motor is higher, making it useful in applications where space and weight are critical factors, especially in aerospace applications

The control of BLDC motors can be done in sensor or sensorless mode, but to reduce overall cost of actuating devices, sensorless control techniques are normally used. The advantage of sensorless BLDC motor control is that the sensing part can be omitted, and thus overall costs can be considerably reduced. The disadvantages of sensorless control are higher requirements for control algorithms and more complicated electronics [[3](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3231115/#b3-sensors-10-06901)]. All of the electrical motors that do not require an electrical connection (made with brushes) between stationary and rotating parts can be considered as brushless permanent magnet (PM) machines, which can be categorised based on the PMs mounting and the back-EMF shape. The PMs can be surface mounted on the rotor (SMPM) or installed inside of the rotor (IPM) , and the back-EMF shape can either be sinusoidal or trapezoidal. According to the back-EMF shape, PM AC synchronous motors (PMAC or PMSM) have sinusoidal back-EMF and Brushless DC motors (BLDC or BPM) have trapezoidal back-EMF. A PMAC motor is typically excited by a three-phase sinusoidal current, and a BLDC motor is usually powered by a set of currents having a quasi-square waveform .

Because of their high power density, reliability, efficiency, maintenance free nature and silent operation, permanent magnet (PM) motors have been widely used in a variety of applications in industrial automation, computers, aerospace, military (gun turrets drives for combat vehicles) , automotive (hybrid vehicles) and household products. However, the PM BLDC motors are inherently electronically controlled and require rotor position information for proper commutation of currents in its stator windings. It is not desirable to use the position sensors for applications where reliability is of utmost importance because a sensor failure may cause instability in the control system. These limitations of using position sensors combined with the availability of powerful and economical

microprocessors have spurred the development of sensorless control technology. Solving this problem effectively will open the way for full penetration of this motor drive into all low cost, high reliability, and large volume applications.

The advantages of BLDC motors over brushed DC motors are:

* High efficiency
* More reliable and no arcing on commutation – no brushes to maintain
* Higher speed and power to size ratio
* Heat is generated in stator – easy to remove
* Lower inertia – no commutator
* Higher acceleration rate