Fundamental Principles of Electric Motor Control Systems

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Abstract: This paper describes the fundamental principles of electric motor control systems as an electromagnetic device that converts electrical into mechanical energy. The first electric motor was invented by William Sturgeon in 1832, while the first commercially successful electric motor was created in 1873. Today, electric motors can be found in a variety of appliances including domestic apparatus, industrial machines, mining, agriculture, transportation systems, and other applications. An electric motor is an electrical machine that converts electrical energy into mechanical energy. Most electric motors operate through the interaction between the motor's magnetic field and electric current in a wire winding to generate force in the form of torque applied on the motor's shaft. The AC Motors, Speed and Torque Control, DC Motors, Brushless DC (BLDC) Motors, Stepper Motors overview of data conversion, ADC and DAC data converters, communication bus to Micro Controller Units (MCU), and their functions and are described.

Keywords: AC Motors, Speed and Torque Control, DC Motors, BLDC, Stepper Motors overview of data conversion, ADC, DAC, MCU

1. Introduction

In everyday life electric motors surround the lives of all professional and not professional individuals, so that can everybody use them at home, office, industry, traffic, and almost no place where people can find them or use them. These electric motors can be used as a home elevator (lifts), some kitchen machines, hand-held watches, cell phones (in the mode of vibration instead of ringing), scanner, printer, plotter, robot, and other possibilities, as shown in **Figure 1.** Depending on electrical power supply motors can be divided into two common groups AC (Alternate Current), which are using high voltage power, and DC Motors (Direct Current), which are using a different kinds of rechargeable batteries making them more portable to use. Two main types of DC motors are brush DC and brushless DC motor. Brush DC motor uses an internal power supply with stationary magnets, while Brushless DC motors use rotation permanent magnet. In the next stage will be introduced other divisions of motors such as:

1. Stepper Motors A stepper motor is a brushless DC motor that drives full rotation into multiple steps The motor's position can move and hold at one of these steps without any feedback sensor Stepper motors are used in Floppy disk drives, plotters, CD ROMs, scanners and many other appliances.

2. Servo Motors are used in servomechanisms. A Servomechanism is an automatic device that uses error sensing to improve machine performance Servo Motors are capable of producing 8,000 to 70,000 RPM for high torque requirements in special design applications

Figure 1. Different Types of Motor's Practical Usage

Figure 2. Different Type of AC Motors

Energy efficiency, mobility, and security are the main challenges facing modern society. The motor control solutions address all of these needs, providing outstanding reliability, excellent quality, and leading-edge innovations. Thus, it is a goal of everyone involved in electrical motor design to consistently increase the computing performance, switching frequency, the figure of merit, accuracy, quality, and reliability, to name only a few of many technical characteristics. As new product generations were released, each of the devices became a benchmark in its own field. But the real beauty lies in combining these individual devices and strengths to create a system, an eclectic motor control system able to set new standards in energy efficiency, dynamic behavior, robustness, and longevity. Finally, it is very that production and consumers have to realize the benefits of efficient semiconductor solutions for electric motor control and drive applications.

2. AC Motors

Modern electrical AC motors are playing a very vital role in everyday life in the house, companies, onboard transportation systems, factories, military divisions, and many other applications. One such equipment which created a giant leap for mankind in both domestic and industrial sectors is the term known as a motor. The usage of AC motors is much more prevalent than DC motors due to several practical reasons which we shall explain later on. Thus, to know what are the different types of AC motors available, to match it perfectly with the demand, it is highly essential to know about their different classifications.

The first type of AC motor is an induction motor, also known as an asynchronous motor, in which two types are shown in **Figure 2,** Domestic low power AC motor **(Left)** and Industrial high power AC motor **(Right).** However, in **Figure 3** is shown the simplified droving of an induction motor **(Left)** and construction of a cage with a shorted rotor **(Right).** This or similar motors are used for kitchen aspirator, low-pressure water pumps, air-conditioners, hairdryer, mixers, vacuum cleaners, fans and other domestic applications where is no need high torque. They are self-starting but because of their relative small power speed control is not used.

The main factor that leads to the adoption and wide motor usage in various fields is its flexibility and huge variety, which can be matched with almost any kind of demand. According to the AC electrical power, all AC motors are systematized in the single-phase and three-phase AC motors. They also can be divided into low, medium, and high power motors. Medium power motors are made as it is illustrated in **Figure 3**.

When heavier load on the shaft of the motor is always present another type of single-phase AC motor is used. They are made as motors with two stator windings, main and auxiliary or starting winding, to provide start with rotating magnetic field. Auxiliary winding provides an additional magnetic field which is shifted by an angle of 90 electrical degrees according to the main magnetic field.

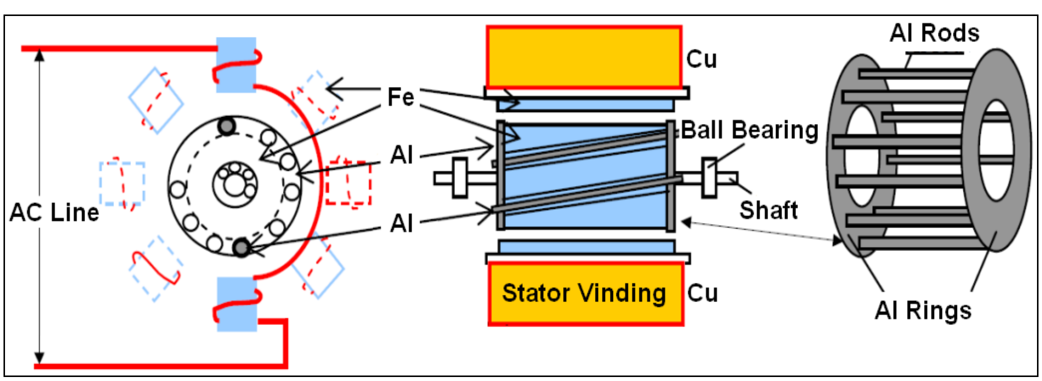


Figure 3. Different Type of AC Motors

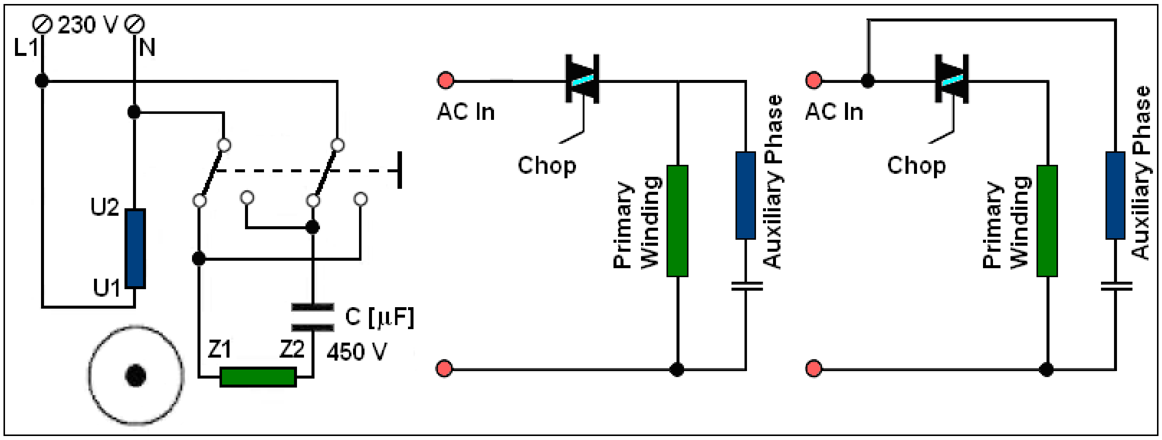


Figure 4. Single Phase Asynchronous Motor and Speed Regulation

Starting rotation the motor, auxiliari winding can be further disenergized (diconnectted). This phase shift can be accomplished using either a capacitor or inductor. Sometimes this starting winding remains connected all the time when the motor is in use, it dependence on motor construction. Synchron speed of the motor is given with relation:

$$V= 120 \cdot f/P \qquad (1)$$

Where values **f =** frequency appliedto the motor; and **P =** number of motor poles.

The asynchronous motor can never reach theoretical synchronous speed, which difference with practical speed is called motor slip. For small power motors, it can reach near 50% of synchronous speed, while for moderate and high power motors it is 2-5%. The voltage to frequency ratio V/Hz is the additional data that has to be taken into consideration.

3. Speed and Torque Control

Control of motor speed (velocity) and torque are operating selections available to most basic DC drives and to some type of AC drives. The two primary ways to control the speed of a single-phase AC motor is to either change the frequency of the line voltage the motor sees or by changing the voltage seen by the motor, thereby changing the rotational speed of the motor. An inverter will convert the AC waveform into a DC voltage and they create a PWM signal output that will filter into a waveform with a predetermined voltage (controlling torque) and frequency (controlling speed).

At this point, let start with a schematic diagram for a single-phase asynchronous motor with auxiliary winding that provides possibilities to change the direction of rotor rotation, which is illustrated in **Figure 4 (Left).** The capacitor connected in series with auxiliary winding serves to make an additional phase shift. The value of this capacitor dependant on rated motor power and its primary task is to initialize rotor rotation. To reduce the speed of rotor rotation motor needs to provide lover voltage applied to the main winding. This will need to decrease magnetic flux in the main winding and increase slip, which will decrease torque as well.

However, to overcome this disadvantage auxiliary phase remain still energized at full mains voltage with certain principles of speed regulation. More exactly mains voltage is chopped by TRIAC and setting phase angle of conduction, what in the other word means regulation of the average value of the voltage of the main phase winding. This has a direct influence on the main phase magnetic flux. Even the shape of voltage on the primary phase is not sinusoidal current that passing thru becomes near sinusoidal shape because motor acts as low-pass filter. The TRIAC Phase-Control design is simpler. There is a single switch that is in line with the AC line. It chops the AC waveform causing the power to shut off during a portion of the AC cycle.

In **Figure 4 (Middle)** is depicted the general schematic for a TRIAC controlled drive. The motor shown is a permanent split capacitor motor having 2 windings and a capacitor for phase shift. The performance can be enhanced by moving to a 3-Wire approach.

However, in **Figure 4 (Right)** is illustrated fan being driven by a 3-wire circuit topology. The auxiliary winding is connected directly to the AC line maintaining full voltage as the RMS across the primary is reduced. Another method for speed regulation is frequency regulation. As stated above, the synchronous speed of rotation is given by speed (V), however, after altering the frequency, rotation of rotor will change in the same manner.

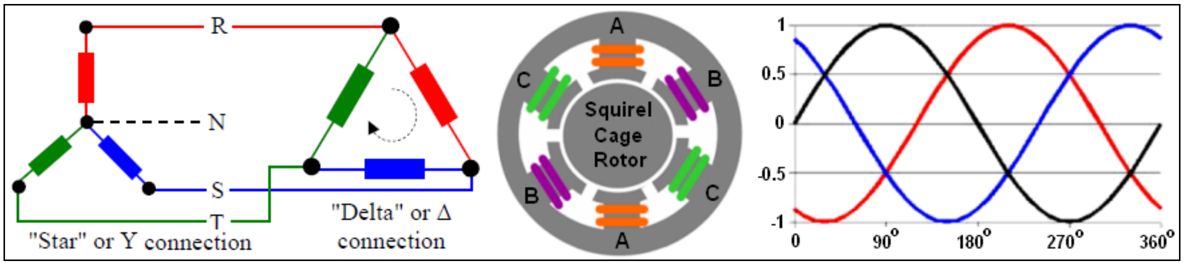


Figure 5. Three-phase Asynchronous Motor and Amplitudes

The next type of AC motor commonly used is a three-phase AC motor, which uses well-known Tesla's rotating magnetic field and stator windings pulled off by angular 120°, shown in **Figure 5 (Left).** Stator's windings can be connected in Y or Δ mode, while the second connection can be reconnected to operate in Y configuration to rotate with reduced speed. This mode is used for the possibility to start the motor without twitch to accelerate until riches speed defined by reduced voltage. After reconnecting windings in delta order, motor accelerates up to the nominal speed-rated on full voltage.
In **Figure 5 (Middle)** is shown cross-section of 3-phase AC motor and in Figure 5 (Right) is shown it's the amplitudes (the black one is just in case of single-phase motor).
Separate speed and torque regulations are now possible thanking industrial electronic and microcontrollers applied in control unit. New generation of power Insulated Gate Bipolar Transistor (IGBT) offers flexibilities in design control logic and the control units, which combines both best characteristics of MOSFET and bipolar transistor, shown in **Figure 6 (Left).**
It is used in output drive stages, needs low power in the gate circuit and it is capable to handle the large voltage and current ranges that requires intensive cooling when operates in a wide range of power regulation. A large heat sink and small DC brushless fan will do the job in most applications. As stated, before motor speed is directly proportional to frequency applied. For medium and small power motors there are available on the market designed frequency, speed regulators, shown in **Figure 6 (Right).**

4. DC Motors

Fleming's left-hand rule explains the principle of DC motor function, illustrated in **Figure 7 (Left),** and in **Figure 7 (Middle)** is explained the practical function of commutator and brushes as parts of the rotor. Construction of DC motors can be either with permanent magnet or field winding in stator. **Figure 7 (Right)** shows the motor with a permanent magnet in the motor stator. Speed control for these motors is obtained altering the current through the rotor. In the next context will be discussed DC motors with both windings in stator and rotor:
1. Wound motor has one voltage supply, and the field winding is connected in series with the rotor winding, which has poor speed regulation. It delivers increasing torque with increased motor current but this is at the expense of speed, which falls with increasing torque demands. It has a very high starting torque because of zero back Electro-Motive Force (EMF) at zero speed, however as the speed builds up the back EMF causing a reduction in torque. Increasing the load on the motor tends to slow it down, but this in turn lowers back EMF and increases the torque to accommodate the load. Speed control is possible by varying the supply voltage. Under no-load conditions, the speed will accelerate to dangerous levels with the possible destruction of the motor, which can be reversed by reversing the connections on either the field or the rotor windings but not both. Applications range from cheap toys to automotive applications using both high and low power.

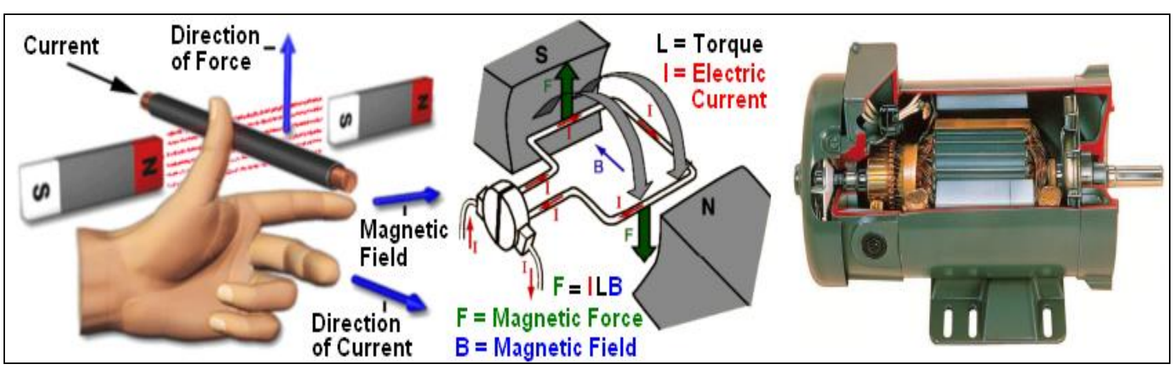


Figure 7. Fleming's Left Hand Rule and DC Motor

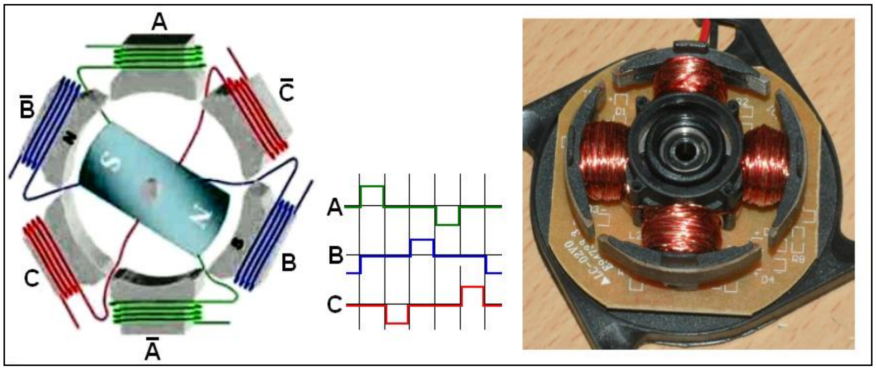


Figure 8. BLDC Motor and Permanent Magnet Rotor

2. Shunt-wound motor also has only one voltage supply to the motor but in this case, the field winding is connected in parallel with the rotor winding. Its speed can be controlled to a limited extent without affecting the supply voltage by the "field weakening". A rheostat in series with the field winding can be used to reduce the field current. This in turn reduces the flux in the air gap and since the speed is inversely proportional to the flux, the motor will speed up. However, the torque is directly proportional to the flux in the air gap so that the speed increase will be accompanied by a reduction in torque. This motor turns at almost constant speed if the voltage is fixed and can deliver increasing torque, without an appreciable reduction in speed, by increasing the motor current. It can be reversed by reversing the connections on either the field or the rotor windings. It serves fixed speed applications such as automotive windscreen wipers and fans.
3. Separately excited motor has independent voltage supplies to the field and rotor windings allowing more control over the motor performance with voltage control of speed and torque of a separately excited motor. Its applications are train and automotive traction.

5. Brushless DC (BLDC) Motors

Current BLDC motors are rapidly gaining popularity and are used in industries such as appliances, aerospace, automotive, consumer, medical, industrial automation equipment, and instrumentation. As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated, which is illustrated in **Figure 8 (Left).** BLDC motors have many advantages over brushed DC motors and induction motors. A few of these are: better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation, higher speed ranges, etc. In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors. In most construction-permanent magnet rotor is situated outside the stator windings, which is shown in **Figure 8 (Right).** One solution to control BLDC motor is shown on bloc schematic in **Figure 9,** which shows how is speed regulation realized by the implementation of Hall Effect sensors attached below the magnetic rotor.

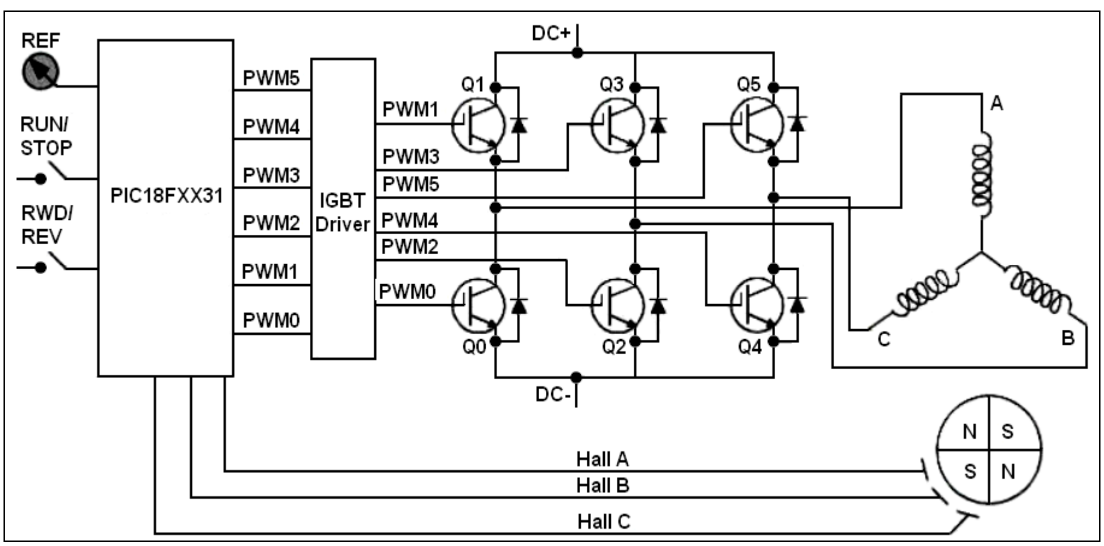


Figure 9. Block Diagram of BLDC Motor

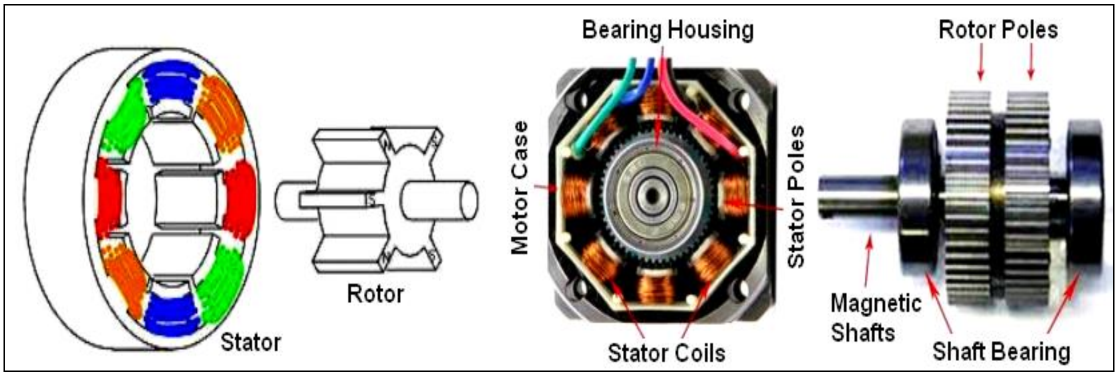
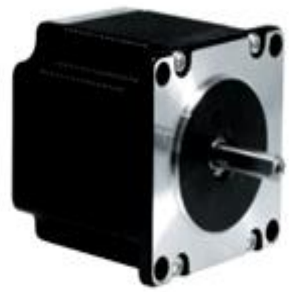


Figure 10. Block Diagram of BLDC Motor

The microcontroller counts impulses from Hall sensors and after comparing them with programmed values regulates pulse width for each stator winding, causing increasing or decreasing the speed of the rotor. In **Table 1** is presented a comparison of characteristics for different types of DC motors.

Table 1. Types of DC Motors

Brushed DC	Brushless DC	Stepper
		
Advantages	***Advantages***	***Advantages***
• Cheapest and simplest motor • Speed linear to applied voltage • Simple motor control	• High efficiency • Little to no maintenance • Long life span • High output power per frame size	• Accurate position control • Excellent low speed torque • Long life
Disadvantages	***Disadvantages***	***Disadvantages***
• High maintenance • Low life-span (due to physical wear on brushes)	• More complicated motor control • Large initial costs	• Low efficiency • Prone to resonances, noise, and torque ripple • Cannot accelerate loads rapidly

6. Stepper Motors

Striper motor serves for accurate positioning. Unlike others, DC motors stepper motor doesn‘t rotate linearly but in steps (one or incremental step by step). The angle of rotor movement depends on the construction of motor i.e. of a number of stator vindings per “ phase“. For each step, it is necessary to apply the next impulse to other winding. There are two types of stepper motors, “unipolar” and “bipolar”. In **Figure 10 (Left)** is illustrated the main principle of its construction and in **Figure 10 (Right)** is illustrated a stepper motor disassembled to see real construction.

The difference between them is the mode of winding connection to the controller, which diagram is shown in **Figure 11.** At this point, there is a lot of variation of stepper motor controllers, from very simple trough truly sophisticated, which main types are: the first is poor experimental or amateur version and the second is a little bit much more serious version.

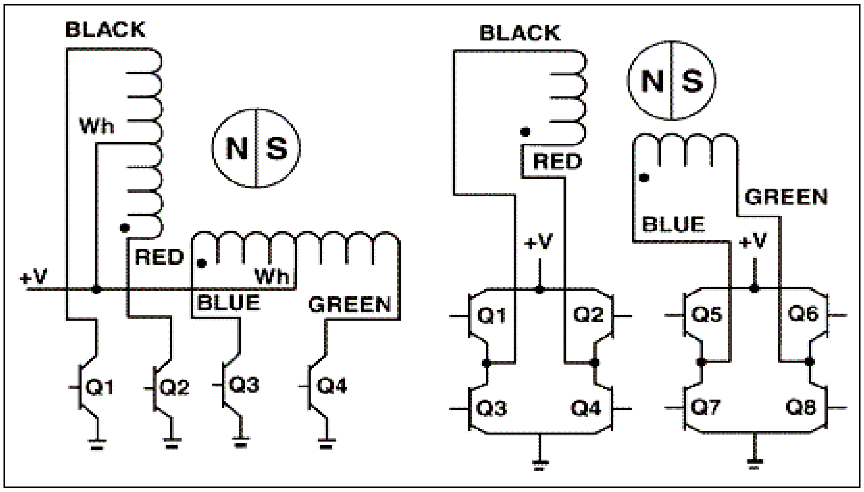


Figure 11. Unipolar and Bipolar Stepper Motors

7. Conclusion

The engineering solution used to calculate the viability of electric motor control design to an application must balance the energy savings with the possible increased cost of more horsepower and increased cost of protection and motor control equipment. The different consumers of these electric motors have to contact the customer support of the manufacturer to determine specific product requirements. In fact, they also must verify that the suggested combination of equipment meets all the applicable safety codes. Applications using electric motor control have already demonstrated that the technology for control and protection of these motors has been proven in many countries worldwide. New equipment using electric motor control will comply with the protection and control standards, but care must be taken that the proper protection and control be applied in motor replacement situations.

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Prof. Dimov Stojce Ilcev is a research leader and founder of the Space Science Centre (SSC) for research and postgraduate studies at Durban University of Technology (DUT). He has three BSc degrees in Radio, Nautical Science and Maritime Electronics and Communications. He got MSc and PhD in Mobile Satellite Communications and Navigation as well. Prof. Ilcev also holds the certificates for Radio operator 1st class (Morse), for GMDSS 1st class Radio Electronic Operator and Maintainer and for Master Mariner without Limitations. He is the author of several books in mobile Radio and Satellite CNS, DVB-RCS, Satellite Asset Tracking (SAT), Stratospheric Platform Systems (SCP) for maritime, land (road and railways), and aeronautical applications.