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Brushed DC Motor Drives for Industrial and Automobile Applications with Emphasis on Control Techniques: A Review

[1]Raghvendra Dhar Diwan,

[1]Lecturer,
[1] Department of Electrical Engineering,
[1]NMDC DAV Polytechnic, Dantewada, C.G.,India

Abstract: The current research provides an in-depth examination of AC to DC and DC to DC converters for brushed DC motor drives. A variety of various AC to DC and DC to DC topologies and control strategies for brushed DC motor drives are described. This detailed literature analysis reveals the benefits, drawbacks, and limitations of numerous topologies and control strategies, as well as the underlying working principles of various topologies and control systems.

I. INTRODUCTION

DC motors have been in use for many decades. The DC network was the first electric network designed and was built to work on the DC electric network. Due to their high-speed functioning and reduced space and weight, AC motors now make up the majority of industry installed motors. Furthermore, due to their structure, AC motors require less maintenance and are less expensive than DC motors. However, DC motors are still employed for a variety of reasons, including their wide speed range, starting and accelerating torques exceeding 400% of their stated values, good speed regulation, and simpler and less expensive control systems. Their primary uses include pulp, paper and paperboard manufacturing, electric vehicle propulsion, textile industries and public transit systems such as underground and tram systems.

Power electronic devices are used in modern DC motor drives, which are separated into chopper-fed and controlled thyristor-fed drives.DC motor drives are classified based on how they handle the energy created during braking of the DC motor [1-4]. In that sense, non-regenerative and regenerative DC drives exist in industry. Non-regenerative DC drives are the most common and commonly utilised type. They can only control motor speed and torque in one direction, which implies they can only operate in the first of four quadrants of operations, as shown in Figure1.

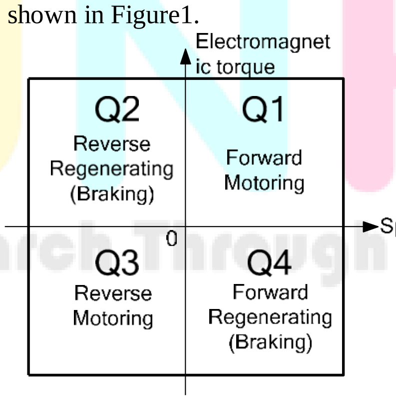

Figure 1. Quadrants of operation of a DC motor

The particular capabilities of regenerative drives are only available when operating in the second and fourth quadrants. The motor torque, which opposes the direction of motor rotation, provides a braking force in these quadrants. A high-performance regenerative drive has the capacity to rapidly move from braking to motoring modes and vice versa, while managing the direction of motor rotation at the same time. A DC regenerative drive is essentially a hybrid of two DC drives that allow the motor to operate in the first and fourth quadrants, or the second and third quadrants, respectively.

The speed of a DC motor can be controlled using armature control, field control, and a combination of both. In the armature control method, the current in the field is kept around the same and the current in the armature is changed by a control signal from the controller, like a PI controller. This method keeps the field current constant, which means the flux density stays the same and the field flux stays the same in the circuit. So, the motor's torque is directly related to the armature current, which can be changed easily by changing the voltage. In the combined armature/field control method (for a separately excited DC motor) the speed can be changed from zero to the rated value, mainly by controlling the voltage in the constant torque/hyperbolic torque area. To increase the speed above the rated value, you need to reduce the field flux in the region of constant power. The combination of armature/field speed control with torque/power is shown in Figure 2.

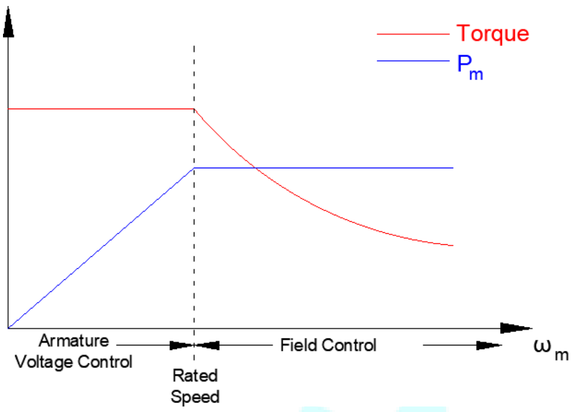

Figure 2. Combined armature and field control of DC motor

In order to implement a full DC motor drive, it is necessary to develop a controller that will control the power circuit, and there are many ways to do this, the most common being:

- Classical PID controllers
- Intelligent controllers

The present work is the result of a thorough literature review, revealing advantages, disadvantages, and limitations, as well as providing the fundamental operating principles of different topologies and methods of control. Since this is a review paper and there is no way to guarantee that all literature available around the world on this topic was taken into account, and there is a risk that the review may be biased.On the one hand, they outline the DC motor drive topologies, and on the other hand, they look at the control techniques according to the most common categorization mentioned above.

II. Topologies of DC motor drives

As mentioned above, DC motor drives can be divided into controlled rectifier-fed and chopper-fed

2.1Controlled Rectifier-fed DC Drives

The main use of a thyristor based DC drive is to control DC motors that are equipped with brushes. In applications where maintenance is higher but not unbearable, the speed control is achieved by feeding the motor armature with a low impedance adjustable DC voltage via the thyristor based rectifier. Usually, a three phase system is used to supply power to the rectifier, but a single phase system can be used when the motor power reaches up to several kilowatts. When supplying power to the field winding, a single phase system is used, as the required power is much lower than the armature power.

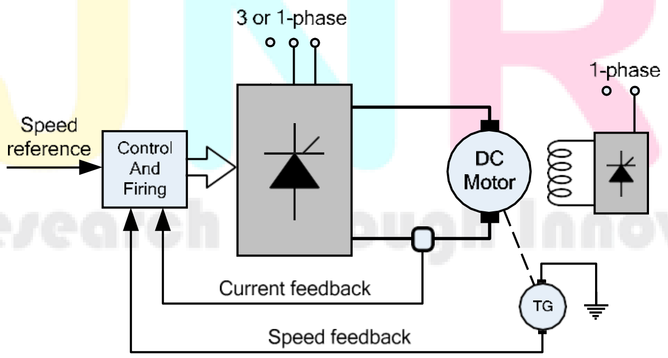

Figure 3. General closed-loop controlled rectifier-fed DC motor drive.

Main power circuit typically consists of 1 or 4 or 6-Thyristor circuit that rectifies the incoming AC supply to generate DC supply to motor armature by changing firing angle of thyristor /s. The mean value of rectified voltages can be varied to control the motor speed. The regulated rectifier produces DC bus with explicit ripple in output voltage. The ripple component causes pulsing current and flux in the motor. Motor poles and motor frame should be laminated material to prevent excessive eddy current loss and commutation issues. It is customary that motors supplied for thyristor drive use laminated construction motors. However, older motors usually have solid pole and/or frame so these motors may not always work well with rectifier based power supply. Drive motors are also commonly supplied with a blower motor attached as standard. This provides continuous ventilation and allows the motor to operate continuously at maximum torque and minimum speeds without over-heating.

Figure 4 shows a DC motor that is separately excited. In this example, the power supply is fed by a single phase half wave converter which can drive a DC motor, allowing it to be used in only one quadrant. This type of drive is suitable for small DC motor with rating power <0.5 kW and the average output voltage of this converter is

$$V_o = \frac{V_m}{\pi}(1 + \cos\alpha), \text{ for } 0 < \alpha < \pi$$

where V_m is the maximum value of the applied line voltage, and a is the firing angle.

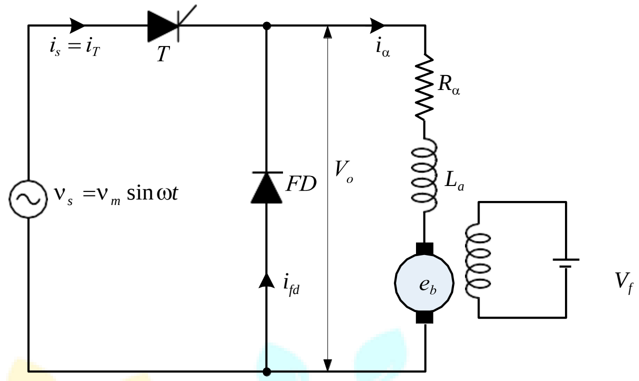

Figure 4. Single-phase half wave converter drive

Figure 5 shows a separately excited motor that is fed with electric power by a single phase asymmetrical converter. Since the diodes of the structure shown in Figure 5 cannot have a positive voltage at any time across their terminals, this means that the motor's armature voltage cannot be negative. As a result, this topology is not regenerative and can only operate in the first quadrant. It is also not suitable for DC drives with a total power of 15 kW. To protect the circuit against overvoltage, the diodes used should be ultra-high speed, with the aim of providing a reliable freewheeling route for the primary power circuit. In case of one quadrant operation, fully controlled converters show the worst characteristics compared to half-controlled converters. In particular, they have more harmonious distortion of the input current, higher cost of control circuits, a lower power factor and a lower mean value of output voltage for the equivalent firing angle. In continuous operation mode, the average output voltage is

$$V_o = \frac{V_m}{\pi}(1 + \cos\alpha), \text{ for } 0 < \alpha < \pi. \qquad (2)$$

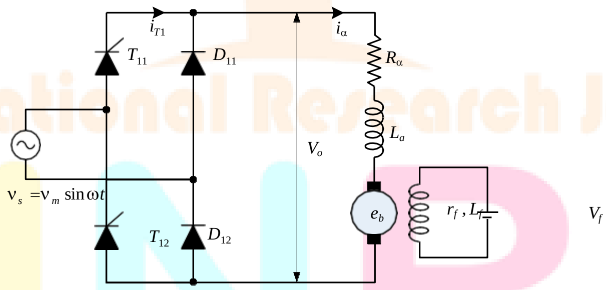

Figure 5. Single-phase half-controlled asymmetrical converter drive.

Figure 6 shows a full wave converter. The upper limit of the armature voltage for this converter type is +2Vm/π, and the lower limit is −2Vm/pi. Therefore, this converter type works in the first quadrant and the fourth quadrant. This converter type is only suitable for motors with a power output of 15 kW or more. The output voltage of the full wave converter can be represented by the following equation:

$$V_o = \frac{2V_m}{Pi}\cos\alpha, \text{ for } 0 < \alpha < \pi. \qquad (3)$$

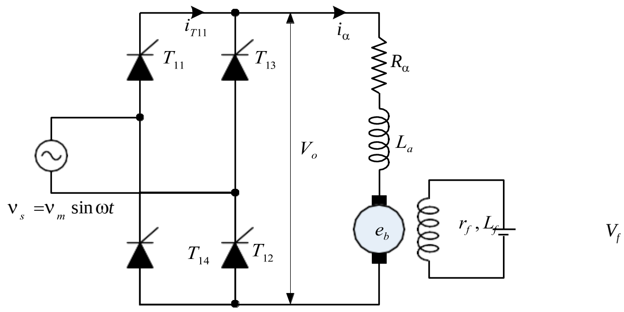

Figure 6. Single-phase fully-controlled converter drive.

Figure 7 shows a single phase fully controlled dual converter drive. Here, two single phase full wave converters are connected back to back. The first full wave converter provides the armature with +Vo and can operate in the 1st and 4th quadrants. The second full wave converter delivers the armature with −Vo and works in the 2nd and 3rd quadrants. This single phase dual converter is a 4 quadrant converter providing the 4 modes of operation: motoring mode, forward braking mode, forward regeneration mode, reverse motoring mode, reverse braking mode, or reverse regeneration mode.

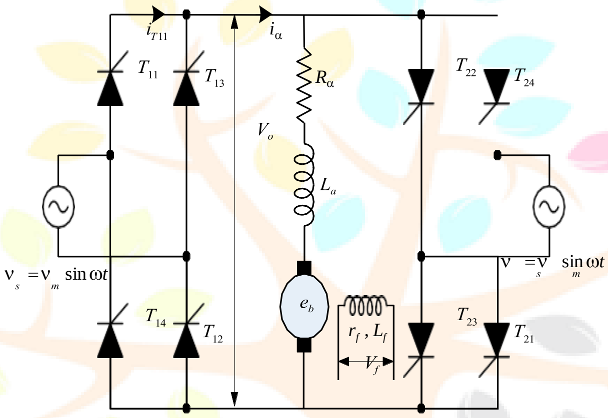

Figure 7. Single-phase fully-controlled dual converter drive.

The output voltage for the first, assuming that it operates at a firing angle α_1, is

$$V_o = \frac{V_m}{\pi}(1 + \cos\alpha_1), \text{ for } 0 < \alpha < \pi. \quad (4)$$

In the same way, the output voltage for the second converter which operates at a firing angle α_2 then is

$$V_o = \frac{V_m}{\pi}(1 + \cos\alpha\ ). \quad (5)$$

In this case, the inversion can be achieved by a field reversal, which means the CEMF (counter electromotive force) of the motor is reversed. Finally, the inversion is achieved by the inversion of the motor's armature current, and the advantage of the inversion over the armature's current is that the inversion is more rapid. The DC motor drives offer the most dynamic response to change in torque or change in speed commands. Continuous armature current: One of the desirable characteristics that leads to a good control system operation is the continuity of armature current, which is a desirable characteristic for the good control system operation.

If you include an extra inductance in a series of motor armatures, you will be able to achieve continuous current operation, without the assurance that a relatively large inductor would result in continuous current operation for all loads conditions and speed.

2.2Chopper—fed DC motor drives

Chopper devices are used when the goal is to transform a fixed DC voltage output voltage into a variable voltage output voltage. The topology of a helicopter is the same as that of a transformer in an AC current.Choppers are widely used in rapid transit systems around the world, as well as in some other applications such as mine hauling, trolley car, forklift trucks, marine hoist, etc.The main advantages of helicopter drives are their regeneration operation capability, fast response and high efficiency.The semiconductor devices used in helicopter drives are power bipolar junction transistor (BJT), forced commutated thryristor, metal-oxide-semiconductor field-effect-transistor (MOSFET), insulated-gate bipolar transistor (IGBT), metal-controlled thryristor and gate turn-off thryristor (GTO).

Regardless of the combination used, the device really works like a switch. When the switch is in the "on" mode, the current passes through the load, and the on-state voltages drop on the Power semiconductors are between 0.5V and 2.5V across them. The power losses can also be determined by taking into account the switching characteristics of the converters

(2–6). Converters can be divided into two groups based on the mode in which they transit between one switching state and another. Converters in these categories are: Hard-switching Converters& Soft-Switching Converters.

III. A comparison of DC motor drives

Industrial applications such as Printing, Mining, Cranes and Metal Shaping applications often require DC drives that are fed by controlled rectifiers. If the converter is designed to supply motors with power up to a couple of kilowatts, then both three phase and single phase mains can be used. On the other hand, if the application involves larger motors with power above 15 kW, then traditional three phase can be used as the main supply. Standard compact converters come in sizes ranging from 0.05 kW to several hundred kW.

The types of controlled rectifiers available are differentiated depending on the application. Single phase controlled rectifiers are divided into one-dimensional, two dimensional and four dimensional topologies.

For 1-Quadrant Converters, Half Wave Topology and Asymmetrical Semi-Converter are produced. The 1Q half wave topology is used for DC motors with 0.5kW and 15kW. The asymmetrical one has important characteristics compared to fully controlled converters, such as: Cheaper control circuits, higher power factor, Higher mean value of output voltage for same firing angle, smaller total harmonic distortion of the current on the input side. Full wave converters for 2Q topology are better suited for applications of up to 15kW, while single phase dual converters are the best choice for 4Q operation up to 15 kW.

Choppers on the other hand are widely used around the world, particularly for fast transit systems. Their high efficiency, rapid response and regeneration capability have made them a viable alternative to the traditional controlled rectifier converter in a lot of DC applications. They also have a low motor loss and torque ripple as a result of the low armature rippled current, which is a result of the high switching frequencies.

Choppers fall into two main categories: hard switching and soft switching. Both types of converters can operate in 1, 2 or 4 quadrants. Hard switching choppers use semiconductor switches such as Goto Operators (GTOs), Bij Circuit Transistors (BJT), Micro Circuit Transistors (MCTs), Micro Electrical Conductors (MOSFET), Thiarchors (GBTs) and Integrated Circuit Transistors (IGBTs) depending on the desired frequency and DC motor power. If the switching frequency is low, up to a few hundred Hz and the power requirements are high, then the use of TGBTs and TGBTs are used.

IV. RESULTS AND DISCUSSION

This paper provides an in-depth analysis of the fundamental topologies, control methods and techniques used in traditional and contemporary brushed DC motor drives for industrial and automotive applications. Each power circuit topology is presented with its advantages and disadvantages, as well as the control techniques used in each case.

The use of DC motor drives is still in use and has evolved over time due to the unique features of DC motors. Application requirements vary greatly, making drive systems mandatory. Control systems may be less or more complex. The modern industry relies on complex power systems to satisfy the growing demands of society for new products and faster production rates.

The development of advanced control techniques like Fuzzy Logic [FL] and Artificial Neural Network [ANN] has enabled the integration of these techniques into modern, high-standard controllers specialized for high-efficiency motor drives.

Advanced control technologies such as FL (Fuzzy Logic) and ANN (Artificial Neural Network) have matured to the point where they can be integrated into high-end controllers specifically designed for high-efficiency motor drives. In addition, new legislation on eco-design and high efficiency requirements have led to new approaches in the electric motor control domain. The presented paper explains nicely about the various feeds to the DC motor drives and its significance.

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