

AC TO DC & DC TO DC CONVERTERS TOPOLOGIES FOR DC MOTOR DRIVES: A REVIEW OF BASIC TOPOLOGIES

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Abstract: This paper deals with a comprehensive survey on the topic of AC/DC & DC/DC converters for DC Motor Drives. A substantial number of different AC/DC and DC/DC topologies appropriate for DC motor drives are presented. This critical literature review brings out merits, demerits, and limitations besides giving the basic operating principles of various topologies.

Keywords: controlled-rectifiers, choppers; dc motor drives; hard switching; soft-switching;

I. INTRODUCTION

DC motors have been available for nearly 100 years. In fact the first electric motors were designed and built for operation using direct current power. Although AC motors are mainly used in industry for high speed operation (over 2500 rpm) because they are smaller, lighter, less expensive, require virtually no maintenance comparing to their DC counterparts, the latter are still used. The reasons for this are that they exhibit wide speed range, good speed regulation, starting and accelerating torques in excess of 400% of rated, less complex control and usually less expensive drive. Today, DC motors are still used in several applications as in industrial production and processing of paper pulp, textile industries, in electric vehicle (EV) propulsion and in public transport such as TRAM (trolley) and METRO. The control of these motors is usually made of power electronics devices, such as controlled rectifier-fed (thyristor-fed) DC drives or chopper-fed DC drives and because of their simplicity, ease of application, reliability and favorable cost have been a backbone of industrial applications.

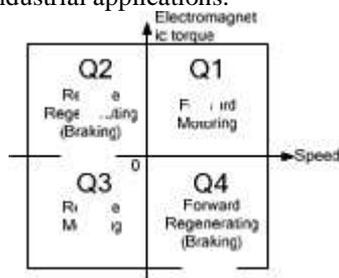


Fig. 1. Quadrants of operation of a DC motor

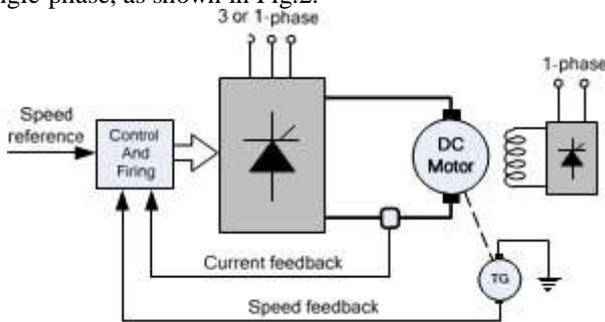
DC motor drives can be categorized according to the way they manage the energy generated during braking of the DC motor ([1]-[4]). In this perspective, there are non-regenerative and regenerative DC drives in industry. Non-regenerative DC drives are the most conventional type in common usage. They are able to control motor speed and

torque in one direction (first-quadrant, Fig.1). With the addition of an electro-mechanical (magnetic) armature reversing contactor or manual switch (units rated 2 HP or less) the controller output polarity is reversed and the same is true for the direction of rotation of the motor armature (third-quadrant, Fig.1). In both cases torque and rotational direction are the same. Regenerative DC drives are also known as four-quadrant drives and they are capable of controlling not only the speed and direction of motor rotation, but also the direction of motor torque. The term regenerative describes the ability of the drive under braking conditions to convert the mechanical energy of the motor and connected load into electrical energy which is returned (or regenerated) to the AC power source. When the drive is operating in the first and third quadrants, both motor rotation and torque are in the same direction and it functions as a conventional non-regenerative unit. The unique characteristics of a regenerative drive are apparent only in the second and fourth quadrants. In these quadrants (Fig.1), the motor torque opposes the direction of motor rotation which provides a controlled braking or retarding force. A high performance regenerative drive is able to switch rapidly from motoring to braking modes while simultaneously controlling the direction of motor rotation. A regenerative DC drive is essentially two coordinated DC drives integrated within a common package. One drive operates in the first and fourth quadrants and the other operates in the second and third quadrants. Another way to classify DC motor drives is according to the type of the converter which is utilized in order to control the speed and the torque of the DC motor ([2]-[4]). When a controlled rectifier circuit (one or three phase) is used the respective category is called: Controlled Rectifier-Fed (Thyristor-Fed) DC Motor Drive. In case that a DC to DC converter is used the respective category is called: Chopper-Fed DC Motor Drive. Both of these categories can further subdivided into non-generative and generative drives based on what was mentioned earlier. In the literature many different converters have been presented and analyzed whose operation is based on controlled rectifier circuits, single-phase or three-phase thus, AC-DC converters ([2]-[9]). These converters can operate at one, two or even four quadrants and are used in various applications depending on the particular requirements. The manufacture of efficient semiconductor switches led to the development of converters which receive as input DC voltage, operating at relatively high frequency (several tens kHz), exhibiting high response speed and are used to control DC motors ([2]-[5], [11]-[26]). In order to

increase further the switching frequency of these DC-DC converters and diminish the ripple current, especially in case of low-inductance DC motors, but also to reduce more the size, weight and volume of the overall drive, soft-switching DC-DC converters have been developed ([11]- [26]). These converters initially have been proposed for switched-mode power supplies ([11]-[15]), but they cannot be directly applied to dc motors, especially for electric vehicle propulsion. Apart from suffering excessive voltage and current stresses ([13], [15]), they cannot handle backward power flow during regenerative braking ([16]). In recent years soft- switching DC-DC converters suitable for DC motor drives have been presented in the literature ([17]-[26]). This paper deals with a comprehensive survey on the topic publications are reviewed and classified into two major categories. Some of them are further classified into several subcategories.

II. CONTROLLED RECTIFIER-FED DC DRIVES

The thyristor DC drive remains an important speed-controlled industrial drive, especially where the higher maintenance cost associated with the DC motor brushes is tolerable. The controlled (thyristor) rectifier provides a low-impedance adjustable DC voltage for the motor armature, thereby providing speed control. For motors up to a few kilowatts the armature converter can be supplied from either Single phase or three-phase mains, but for larger motors three- phase is always used. A separate thyristor or diode rectifier is used to supply the field of the motor: the power is much less than the armature power, so the supply is often single-phase, as shown in Fig.2.



The main power circuit usually consists of a one or two or four or six-thyristor circuit, which rectifies the incoming AC supply to produce a DC supply to the motor armature. The assembly of thyristors, mounted on a heatsink, is usually referred to as the 'stack'. By altering the firing angle of the thyristor/s the mean value of the rectified voltage can be varied, thereby allowing the motor speed to be controlled. The controlled rectifier produces a DC bus with a pronounced ripple in the output voltage. This ripple component gives rise to pulsating currents and fluxes in the motor, and in order to avoid excessive eddy-current losses and commutation problems, the poles and frame should be of laminated construction. It is accepted practice for motors supplied for use with thyristor drives to have laminated construction, but older motors often have solid poles and/or frames, and these will not always work satisfactorily with a

rectifier supply. It is also the norm for drive motors to be supplied with an attached "blower" motor as standard. This provides continuous through ventilation and allows the motor to operate continuously at full torque even down to the lowest speeds without overheating.

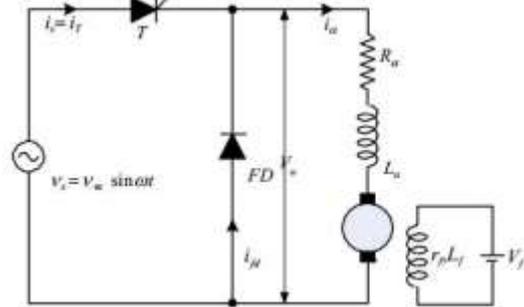


Fig. 3. Single phase half wave converter drive

Low power control circuits are used to monitor the principal variables of interest (usually motor current and speed), and to generate appropriate firing pulses so that the motor maintains constant speed despite variations in the load. The speed reference (Fig.2) is typically an analogue voltage varying from 0 to 10 V, and obtained from a manual speed- setting potentiometer or from elsewhere in the plant. The combination of power, control, and protective circuits constitutes the converter. Standard modular converters are available as off-the-shelf items in sizes from 0.5 kW up to several hundred kW, while larger drives will be tailored to individual requirements. Individual converters may be mounted in enclosures with isolators, fuses etc., or groups of converters may be mounted together to form a multi-motor drive.

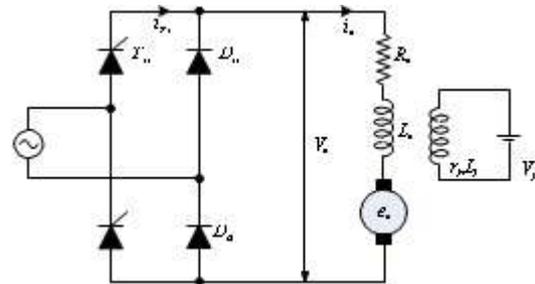


Fig. 4. Single phase half-controlled asymmetrical converter drive

A separately excited DC motor fed through single phase half wave converter ([2]-[6]) is shown in Fig. 3. Single phase half wave converter feeding a DC motor offers only one quadrant drive. Such type of drives are used up to about 0.5 kW DC motor. For this converter the average output voltage can be calculated versus the firing angle α as:

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

where V_m is the maximum value of the applied line voltage A separately excited DC motor fed through a single-phase asymmetrical semiconverter is shown in Fig. 4. The armature voltage cannot be at any instant negative because the diodes cannot have a positive potential difference in their terminals. This means that this converter topology cannot regenerate. Its operation is therefore confined to the first quadrant of the

va-ia (or torque-speed) diagram (motoring mode) and is used up to 15 kW DC drives. The diodes which offer the freewheeling path for the main power-circuit (armature current) should be ultra-high speed diodes, in order to protect the circuit from undesirable overvoltages. For one-quadrant operation, half- controlled converter exhibits better characteristics than the fully controlled one, such as, less harmonics distortion to the input current, increased mean value of the output voltage for the same firing angle, power factor improvement and cheaper control circuits. For this converter type, considering continuous-mode operation the average output voltage can be calculated as ([2]-[6]):

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

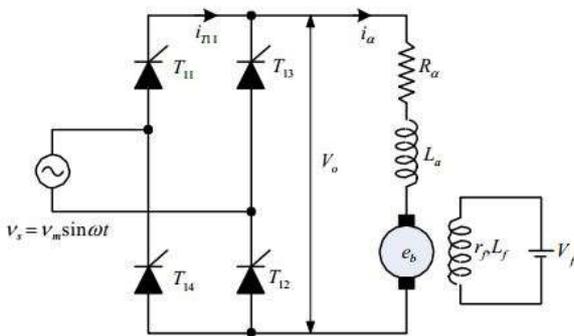


Fig.5. Single phase fully controlled converter drive

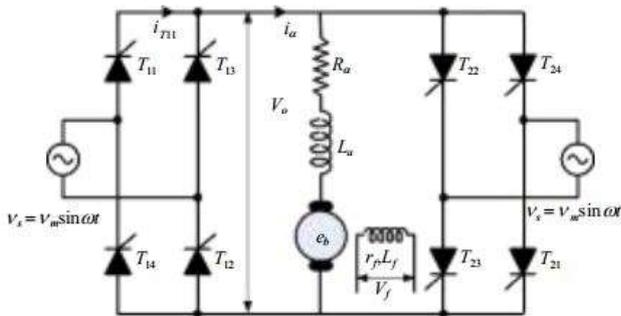


Fig. 6. Single phase dual converter drive

In Fig.5 the armature voltage is varied by single phase full wave converter. It is a two quadrant drive and is limited to applications up to 15kW. The armature voltage can be varied between $+2V_m/\pi$ and $-2V_m/\pi$ and this possibility allows DC operation in the first and fourth quadrant of the v_o-i_a diagram or, in other words, in the first and second quadrant of the torque-speed diagram. The reversal of the armature or field voltage allows operation in the second and third quadrant. For continuous-mode operation the output voltage is:

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

In Fig. 6, there are two single phase full wave converters (in back-to-back connection), either converter 1 operates to supply a positive armature voltage V_o , or converter 2 operates to supply negative armature voltage $-V_o$. Converter 1 provides operation in first and fourth quadrants, and converter 2 provides operation in second and third quadrants.

It is four- quadrant drive and provides four modes of operation: forward motoring, forward braking (regeneration), reverse motoring, and reverse braking (regeneration). If converter 1 operates at a firing angle of α_1 and similarly, if converter 2 operates at a firing angle of α_2 then the armature voltage is

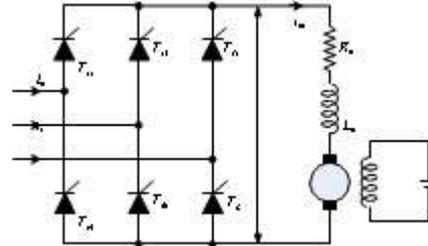


Fig. 7. Three-phase fully controlled converter

It should be noted that in this case, inverting operation occurs by reversing the current flow through the motor armature rather than by reversing the motor counter electromotive force (CEMF), which requires a field-reversal. Thus, the field reversing is not required and much more rapid motor reversal is possible. In addition, the DC motor drives provide the fastest dynamic response to changes in torque or speed commands. The continuity of armature current is a desirable feature for the satisfactory operation of the control system. Continuous-current operation can be obtained by including additional inductance in series with the motor armature circuit, but even a large inductor cannot ensure continuous-current operation under all conditions of load and speed. Other converter configurations, as the three-phase AC to DC converters can be used to reduce the size of the necessary. In Fig. 7 a three-phase fully controlled converter ([2]-[6]) is shown. It is the most popular and frequently used AC to DC converter for large power motor-control applications (up to 140kW). A half-controlled configuration, with three thyristors replaced by diodes is possible, but it can operate only in the $v_o - i_a$ addition it has the disadvantage of introducing even harmonics into the line-current waveforms and is therefore unsuitable for large power applications. For continuous-mode operation the output voltage is:

$$V_o = \frac{3V_{mL}}{\pi} \cos\alpha, \text{ for } 0 < \alpha < \pi \quad (6)$$

where V_{mL} is the maximum value of the line voltage.

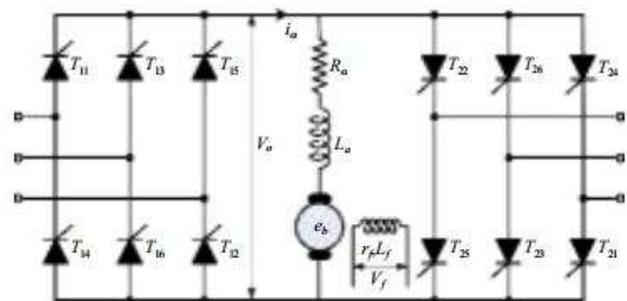


Fig. 8. Dual three-phase fully controlled converter

As in the case of the single-phase fully controlled converter, the three-phase fully controlled converter provides

the possibility for two-quadrant operation (motoring and regeneration or braking modes respectively). If four-quadrant operation is required, the dual three-phase fully controlled converter topology can be used (Fig. 8).

III. CHOPPER-FED DC MOTOR DRIVES

A chopper is a static power electronic device that converts fixed DC input voltage to a variable DC output voltage. It could be considered as DC equivalent of an AC transformer since it behaves in an identical manner. Choppers are now being used all over the world for rapid transit systems. They are also used in trolley cars, marine hoist, forklift trucks and mine haulers. Chopper systems are characterized by high efficiency, fast response and regeneration operation capability. The power semiconductor devices which are employed in these circuits can be force commutated thyristor, power BJT, MOSFET and IGBT. GTO and MCT based choppers are also used. All these devices actually operate like a switch. When the switch is off, no current can flow. Current flows through the load when switch is "on". The power semiconductor devices have on-state voltage drop in the range of 0.5V to 2.5V across them and together with their switching characteristics, their power losses are determined. Depending on the way that the transition from one switching state to another is implemented, the converters are divided in two categories: a) hard-switching converters and b) soft-switching converters.

A. Hard-Switching Converters For DC Drives

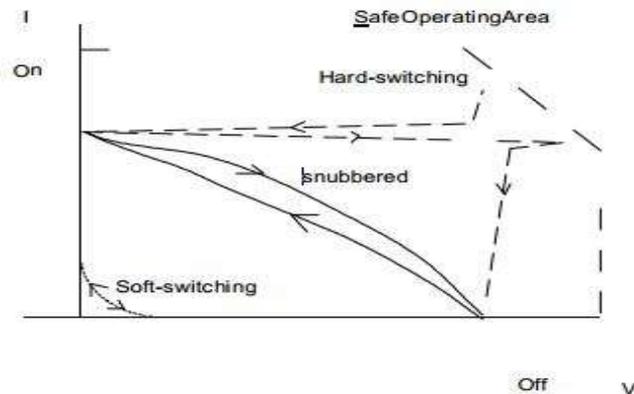


Fig. 9. Hard and soft switching characteristics

Since 1970, conventional PWM power converters have been operated in a switched mode operation. Power switches have to cut off the load current within the turn-on and turn-off time intervals under the hard-switching conditions. Hard-switching refers to the stressful switching behavior of the power electronic devices. The switching trajectory of a hard-switched power device is shown in Fig.9. During the turn-on and turn-off processes, the power device has to withstand high voltage and current simultaneously, resulting in high switching losses and stress. Dissipative passive snubbers are usually added to the power circuits so that the dv/dt and di/dt of the power devices could be reduced, and the switching loss and stress are diverted to the passive snubber circuits. However, the switching loss is proportional to the switching frequency, thus limiting the maximum switching frequency

of the power converters. Typical converter switching frequency was limited to a few tens of kHz (typically 20 kHz to 50 kHz) in early 1980's. The stray inductive and capacitive components in the power circuits and power devices still cause considerable transient effects, which in turn give rise to electromagnetic interference (EMI) problems.

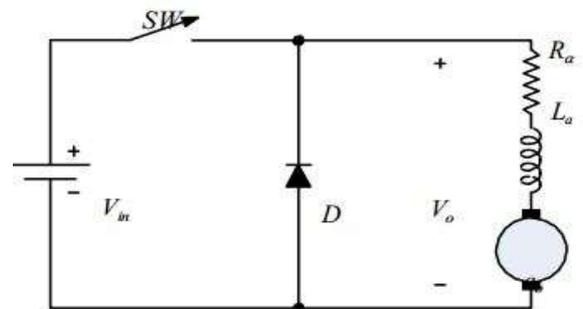


Fig. 10. 1-quadrant hard switching DC motor drive
 A single-switch chopper using a Thyristor, BJT, MOSFET or IGBT is presented in Fig.10. It can only supply positive voltage and current to a DC motor, and is therefore restricted to the first quadrant of (motoring) operation.

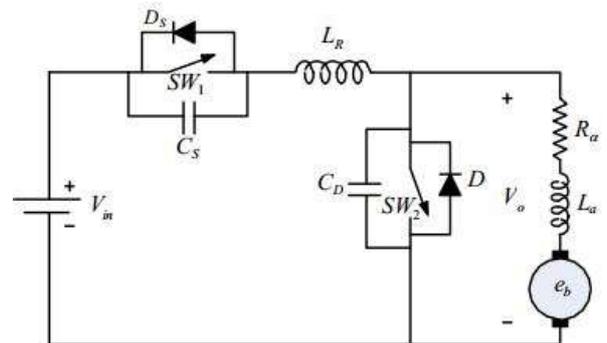


Fig. 12. Zero-voltage multi-resonant converter fed DC motor drive

A two-quadrant (2Q) Zero-Voltage Multi-Resonant (ZVMR) is presented in Fig.12 ([18]). This converter is created by adding a resonant inductor and two resonant capacitors to a conventional 2Q-PWM DC drive. It has been developed for bidirectional power flow for both motoring and regenerative braking DC motor drives. This soft switching converter not only possesses the advantages of achieving high switching frequencies (>100 kHz) maintaining low current ripple of DC motor, with practically zero switching losses due to Zero-Voltage-Switching (ZVS) for all switches, but also provides full ranges of voltage conversion and load variation. The ZVMR converter uses all built-in diodes of the power switches and absorbs all major parasitic. It should be noted that the ZVT technology is highly desirable for power MOSFET based power conversion. It is due to the fact that the power MOSFET device generally suffers from severe capacitive voltage turn-on losses. The 2Q-ZV-MR converter can handle both no-load up to short-circuit condition without any additional measures since it behaves as a constant current source after reaching the maximum output current.

The power rating of the semiconductors (MOSFET) associated with the MR cell are higher as compared with the conventional 2Q-PWM DC drive, due to the circulating energy and the conduction losses.

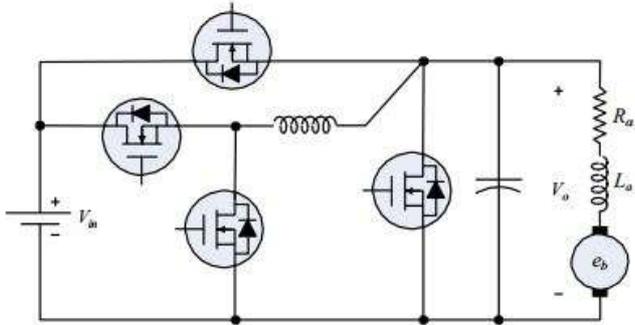


Fig. 13. Zero-voltage-transition converter fed DC motor drive

A two-quadrant (2Q) Zero-Voltage-Transition (ZVT) converter ([19]) is presented in Fig.13. This converter has been also developed for bidirectional power flow for both motoring and regenerative braking DC motor drives. Compared with the conventional 2Q-PWM DC drive, it needs additional components: a resonant inductor, a resonant capacitor and two auxiliary switches. The 2Q-ZVT converter exhibits some important advantages such as: Zero Voltage Switching (ZVS) for all main switches and diodes, unity device voltage and current stress during both the motoring and regenerative modes of operation, simple circuit topology, same resonant tank for both forward and backward power flows, full utilization of all built-in diodes of the power switches. These characteristics lead to the achievement of high switching frequency (>100 kHz), high power density and high efficiency. Also, the operation of this converter requires the use of a DSP system in order to generate the appropriate control signals of the semiconductor switches.

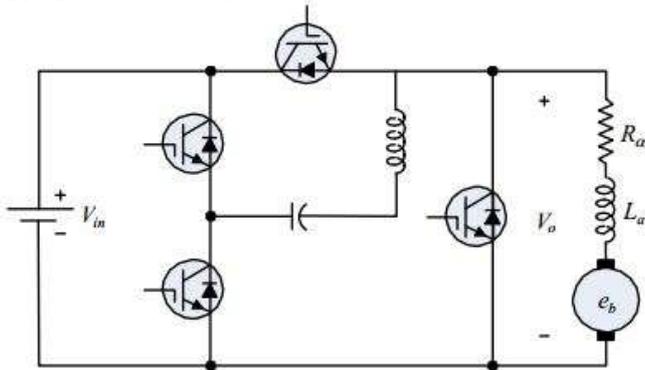


Fig. 14. Zero-current-transition converter fed DC motor drive

A two-quadrant (2Q) Zero-Current-Transition (ZCT) converter ([21]) is presented in Fig.14. This converter also provides bidirectional power flow for both motoring and regenerative braking DC motor drives. The 2Q-ZCT converter, compared with its conventional PWM counterpart, needs additional components: a resonant inductor, a resonant capacitor and two auxiliary switches. The main advantages of this converter are: ZCS for all main and auxiliary switches

and diodes, minimum voltage and current stress, low cost simple circuit topology, same resonant tank for both forward and backward power flows, and full utilization of all built-in diodes of the power switches. All the previous mentioned characteristics lead to the achievement of switching frequency in the range of 50 kHz, high power density and high efficiency.

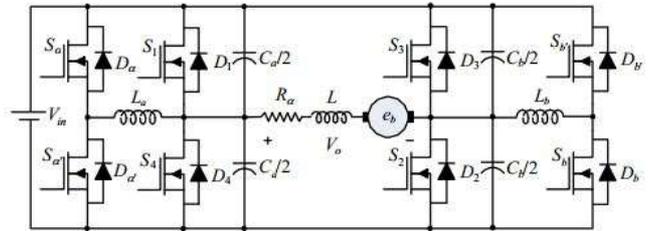


Fig. 15. 4Q-ZVT converter fed DC motor drive

This converter is particularly useful for medium-power DC motor applications (a few kW), employing insulated-gate bipolar transistor (IGBT) as power devices, which generally suffer from diode reverse recovery during turn-on and severe inductive turn-off switching losses. Finally, a DSP system is also required for the proper operation of this converter. A four-quadrant (4Q) Zero-Voltage-Transition (ZVT) converter ([21]-[22]) is presented in Fig.15. This converter has been developed mainly for MOSFETs like its two-quadrant ZVT ancestor, and for motoring and regenerative braking in both forward and reversible operations for DC motor drives. The main advantages of this converter are: ZVS for all main and auxiliary switches and diodes, unity voltage and current stress, low circulating energy and simple circuit topology. Furthermore, the same resonant tank for both forward and backward power flows is used, full utilization of all built-in diodes of the power switches is achieved thus minimizing the overall hardware count and cost. All these lead to the achievement of high power density (up to 5kW) and high efficiency. To achieve ZVS operation, two sets of resonant tanks are utilized: inductor L_a , resonant capacitors $C_a/2$ with auxiliary switches S_a and S_a' for soft switching S_1 and S_4 and inductor L_b , resonant capacitors $C_b/2$ with auxiliary switches S_b and S_b' for soft switching S_2 and S_3 . The DC motor can be considered to be simultaneously fed by two 2Q-ZVT converters as shown in Fig. 15.

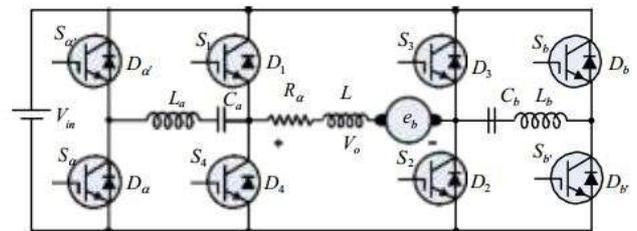


Fig. 16. 4Q-ZCT converter fed DC motor drive

A four-quadrant (4Q) Zero-Current-Transition (ZCT) converter ([22]) is presented in Fig.16. This converter has been developed mainly for IGBTs, like its two-quadrant ZCT ancestor, and for motoring and regenerative braking in both forward and reversible operations for DC motor drives. To achieve ZCS operation, two sets of resonant tanks are required, inductor L_a , resonant capacitor C_a , with auxiliary

switches S_a and S_a' for soft switching of S_1 and S_4 and inductor L_b , capacitor C_b , with auxiliary switches S_b and S_b' for soft switching of S_2 and S_3 . The DC motor can be considered to be simultaneously fed by two 2Q-ZCT converters. Therefore this four-quadrant ZCT converter has the same characteristics as its two-quadrant ZCT ancestor. This topology can be used for high frequency dc motor drive applications up to about 5 kW.

IV. COMPARATIVE EVALUATION OF DC MOTOR DRIVES

Controlled rectifier-fed DC drives remain common in industries, such as metals, cranes, mining and printing. For motors up to a few kilowatts the DC motor can be supplied from either single-phase or three-phase mains, but for larger motors (>15-20kW) three-phase is always used. Standard modular converters are available as off-the-shelf items in sizes from 0.5 kW up to several hundred kW. There are different controlled rectifier circuits available depending on the application. Single-phase controlled rectifiers are classified into one-quadrant, two-quadrant and four-quadrant operation topologies. For one-quadrant operation half wave converters and asymmetrical semi-converters are available. The first converters are used for applications up to about 0.5 kW DC motors while the latter up to 15 kW. For one-quadrant operation, half-controlled converter exhibits better characteristics than the fully controlled one, such as: less harmonics distortion to the input current, increased mean value of the output voltage for the same firing angle, power factor improvement and cheaper control circuits. For two-quadrant operation the full wave converter is the appropriate one for applications up to 15kW. Also, if a four-quadrant operation is needed the single-phase dual converter is the right choice for up to 15kW. Three-phase controlled rectifiers are also classified into one-quadrant, two-quadrant and four-quadrant operation topologies. Although half-controlled 3 Φ converters are available, fully controlled converter is the most popular and frequently used AC to DC converter for large power motor control applications (up to 140kW). A half-controlled configuration, with three thyristors replaced by diodes has the disadvantage of introducing even harmonics into the line current waveforms and is therefore unsuitable for large power applications. Furthermore, half-controlled converter is one-quadrant converter while the fully controlled one is a two- quadrant converter. When a four-quadrant operation is required function a dual three-phase fully controlled converter is also available. Choppers are now being used all over the world for rapid transit systems. They have replaced conventional controlled-rectifier converters in many DC motor applications due to their high efficiency, fast response and regeneration operation capability. Due to the high switching frequency the armature ripple current is decreased and therefore motor losses and torque ripple are also decreased. As it was mentioned in the previous section, choppers are divided into hard-switching and soft-switching converters. Both of these converters are further classified as: one, two or four-quadrant

converters. Hard-switching converters utilize thyristor, GTO, MCT, BJT, MOSFET and IGBT depending on the DC motor power and required frequency. Thyristors and GTOs are utilized for high power applications (up to several hundred kW) and for low switching frequencies (up to several hundred Hz). Power BJTs and mainly IGBTs and MOSFETs are used when high frequency (in the range of 20-50 kHz) and for low to medium power is required. All these choppers usually employ PWM control techniques. When even higher switching frequencies are required, i.e. for low-inductance DC motors, soft-switching choppers can be employed in order to reduce switching losses on one hand and to limit Electromagnetic Interference (EMI) on the other. Furthermore, soft-switching techniques can reduce converter losses and therefore increase converters' efficiency. More specifically, a two-quadrant (2Q) Zero-Voltage Multi-Resonant (ZVMR) converter not only possesses the advantages of achieving high switching frequencies (>100 kHz) maintaining low ripple current, with practically zero switching losses due to Zero-Voltage-Switching (ZVS) for all switches, but also provides full ranges of voltage conversion and load variation. On the other hand, the power rating of the MOSFET associated with the MR cell are higher as compared to the conventional 2Q-PWM DC drive (hard switching), due to the circulating energy and the conduction losses. A 2Q-ZVT converter is proposed as a better solution in place of ZVMR when MOSEFTS are employed or a 2Q-ZCT one when IGBTs are used. The main reasons are that this converter achieves ZVS for all main switches and diodes, unity device voltage and current stress during both the motoring and regenerative modes of operation, simple circuit topology, same resonant tank for both forward and backward power flows, full utilization of all built-in diodes of the power switches. In this way high switching frequency (>100 kHz), high power density and high efficiency are achieved. The 2Q-ZCT converter is intended to be used for medium-power DC motor applications (a few kW) and for switching frequency in the range of 50 kHz, employing insulated-gate bipolar transistor (IGBT) as power devices. Both of the last two soft-switching converters need a DSP system for the proper driving of their semiconductor switches. Finally, 4Q-ZVT and 4Q-ZCT converters are available for MOSFETs and IGBTs respectively. These converters can be used for high frequency DC motor drives and for applications up to about 5 kW. A DSP system is also needed for the proper operation of these converters.

V. CONCLUSIONS

In this paper a review of the basic topologies for DC motor drives is attempted. DC motors are still used in several applications as in industrial production and processing of paper pulp, textile industries and in public transport such as TRAM (trolley) and METRO. DC motor drives are categorized according to the converter it is utilized. The two main categories controlled rectifier (thyristor) and chopper-fed DC drives are presented in order to outline their basic characteristics. Moreover, the basic equations, key

advantages and application fields were attempted to be presented. Both of the previous mentioned categories can further subdivided into non-generative and generative drives and this operation characteristic has been exploited for their comparative evaluation.

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