The Application of Power Electronics in DC Motor Drives

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ABSTRACT

The aim of this report is to summarize my findings on the working of DC Motor Drives with a focus on the analysis of the Power Electronics applications involved and a MATLAB-Simulink to support the findings.

Introduction

Our Micro-controllers and Interfacing introduced me to the concept of Motor Drives and why they are needed as mechanism for isolating low power control units from getting damaged by the relatively high power that Motors consume. We had utilized the popular L298 MOSFET-Based H-Bridge Motor Driver as a part of our project and soon following which we designed a MOSFET-based H-Bridge Motor Driver for our robot entry at the National Engineering and Robotics Competition (NERC).

This gradual progression has served as a motivation to explore how DC Motors are driven, and more specifically learn about how the tools of Power Electronics are utilized in the process. The first section provides in-depth background into the basics of the Power Electronics applications that will be necessary for understanding DC Motor Driver circuits, the second section will give an overview of the basic DC Motor control concepts ranging from one to all four quadrants with respect to the discussed Power Electronics application, and lastly the third section will present a MATLAB-Simulink model of the discussed Power Electronics application to verify & demonstrate some of our findings.

AC to DC Rectification

The scope of this study involves DC Motors that usually require high power such as those in Industrial settings. Most of our transmission to industries happens in AC (Alternating Current). It then becomes essential to have a mechanism to translate power from a 3-Phase AC Source to DC in the most efficient possible manner, which can then be utilized to drive a DC Motor. Rectification circuits help achieve this task.

A DC Motor Drive at its very basic being supplied by a single-phase AC source can be modelled as a circuit containing a diode for basic half-wave rectification, a resistor for current-limiting, and lastly a battery to model a DC Motor's back-emf characteristics. This is shown in figure 1

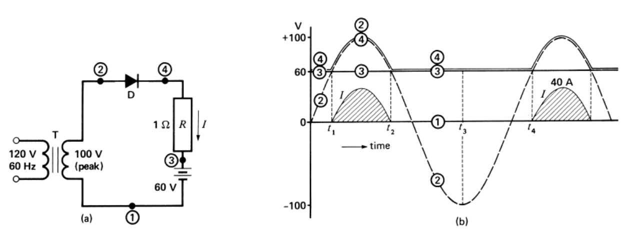

Figure 1. Basic Rectification Circuit. "1" refers to ground, "2" is AC supply's voltage level, "3" is the voltage level of the battery, and "4" is the voltage-level of the AC supply after a small drop across the diode, which can be effectively ignored.[1]

However, we observe that such a circuit not only suffers from I^2R losses due to the current-limiting resistor, but is also is not able to deliver the power $P = VI$ for the full-duration of an AC cycle as consequence of two things: only the positive half of the AC cycle is supplied to the motor and the current during a cycle dies out as soon as the voltage level drops below the voltage level of the battery or motors back-emf. In the case of a motor, such a battery voltage would be held in the form of a back-emf due to inertia, regardless of the gradual drop in supply voltage. This largely limit's average DC voltage and consequently total DC power delivered to the motor. The following equation expresses this voltage conversion relation mathematically,: $E_{31} = E_{DC} = 0.45E_{AC} = 0.45E_{41}$.[1]

Furthermore, the battery-voltage will in-fact lead to a reverse current flow in the circuit, causing a reverse-leakage current across the diode. This is because in principle, once forward-biases, a diode only becomes fully reverse-biased when the current flow through it reach's 0. This reverse flow of current can be undesirable in high-current applications such as the DC Motor. Lastly, such a circuit offers no ability to control any of the variables of a DC Motor such a speed, torque or direction.

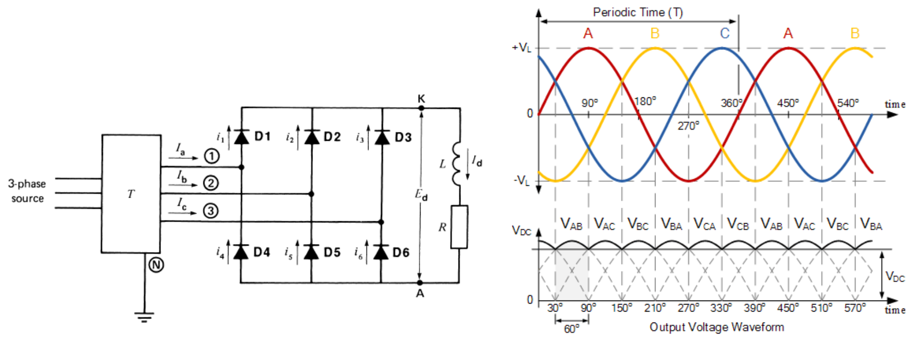

Figure 2. 3 Phase, 6 Pulse Rectifier a) Circuit Diagram b) Voltage Waveform.[1]

Figure 2 show's us an improved version of the circuit that rectifies a 3-phase source, into 6 pulses. This setting of diodes takes into account all three phases, utilizing both the positive and negative AC cycles, allowing to deliver a significantly larger average DC voltage. This can be expressed as: $E_{DC} = 1.35E_{AC}$.[1]

The addition of a filtering inductor allows to store energy in the form of a magnetic field, which is released as current when the rectified AC cycle voltage drops below the battery-voltage. This ensures a smoother current level throughout the supply, increasing the power delivered. It also helps avoid I^2R losses except for those in the motor armature itself.

To solve the issue of control and reverse-current flow, we replace the diodes with thyristors (SCR - semiconductor controlled rectifier). These are devices similar to diodes but operate on a gate-firing principle, in which a small current pulse on the thyristor's gate terminal enables conduction across its anode and cathode given the anode is positive. The phase-angle at which the gate current-pulse is fired allows to control over its conduction and hence, power delivered. This is shown in figure 3b

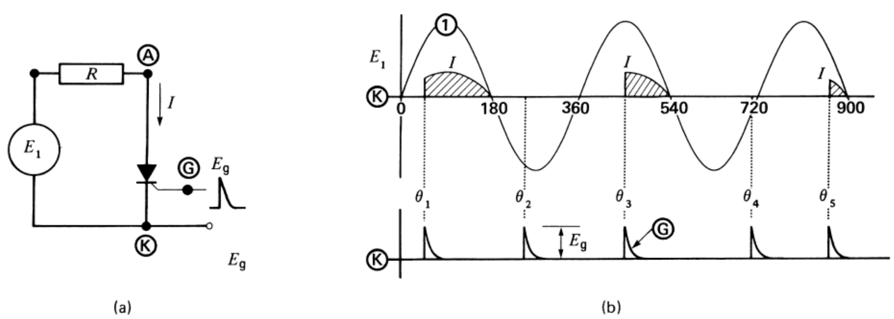

Figure 3. Thyristor's working based on gate-firing principle.[1]

In the setting of an AC 3-Phase 6 Pulse Rectifier, the gate-pulses sent to the thyristors are set in a phase-locked loop (PLL) with one of the AC phases to stay in sync. Each thyristor is successively pulsed to conduct for 120°, starting at a phase-angle of 30° with respect to the PLL phase, while each pair of thyristors (one from each bridge) conducts for 60° simultaneously to complete the circuit. This setting gives us maximum rectification.[2] The animation in appendix figure 8 shows this.

The firing-angle of the successive gate-pulses is said to be 0° in this setting[3]. This firing angle can be varied from 0° to 180 ° with the following relation: $E_d = 1.35\ E_{AC}\ \cos\alpha$, having a decreasingly positive polarity from 0 to 90, and then an increasingly negative polarity from 90 to 180. This is shown in figure 4 and is consistent with our MATLAB-Simulink Model result shown in appendix figure 9.

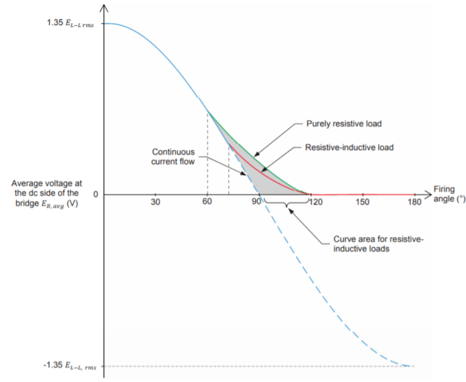

Figure 4. Output voltage vs Firing Angle.[2]

DC Motor Drives

Now that the basic circuitry for driving a separately excited DC Motor has been established, let us explore some DC Motor control concept and see how they are scaled for extending control to all-four quadrants.

1-Quadrant Control

This involves the control of cases when both: the direction of rotation and direction of motor torque are the same. The circuit shown in figure 5 or 7 can be coupled with a control circuit that sends successive gate-triggering pulses at various firing-angles based on external feedback and user-input, allowing control over the DC Motor. These gate-triggering pulses are set to always limit the current I_d below a preset threshold value.

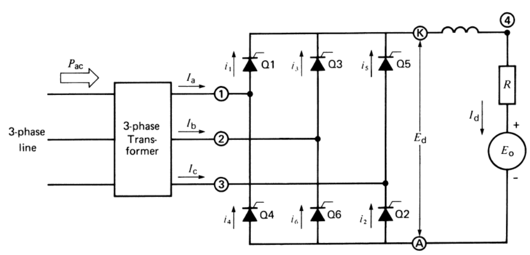

Figure 5. 3 Phase 6 Pulse Rectifier.[4]

The initial firing-angle is set to 90 degrees, as this sets E_d to zero. To accelerate this angle is gradually reduced, allowing I_d to flow, and E_d (motor back-emf + armature drop) and motor torque to build-up. To slow the motor, α is increased, this decreases E_d and cuts off I_d as E_d drops below E_o. The motor is said to **'coast'** to a lower speed, based on its mechanical load and inertial properties. This continues until E_o, the back-emf voltage, gradually reduces to a value below E_d, after which I_d flows and motor torque builds up again.[1]

However, this approach still doesn't offer any control over torque or braking, and is still largely in-efficient. This is because of the consequent voltage and current ripples at higher angles. These introduce armature copper losses and iron losses. In addition, the rectifier also absorbs a very large amount of reactive power at higher firing angles. This is undesirable as it places unwanted stress at the supply line.[4] This consistent with our MATLAB-Simulink Model results shown in appendix figure 10.

Hence, we can conclude that such a form of control is only suited for constant-speed operation at a low-firing angles.

2-Quadrant Control

This form of control introduces the concept of dynamic and regenerative breaking, in which the motor is made act as a generator to a load, allowing it to loss speed rapidly. Dynamic breaking simply involves loading the motor armature across a resistor, while regenerative braking involves feeding back to the supply-line.

This is done by making the rectifier act as an inverter by delaying the firing-pulses by greater than 90 degrees, this reverse the polarity of E_d and reversing the armature field E_o manually. This allows a current to flow in the reverse direction, rapidly slowing the motor. The greater the firing angle is increased beyond 90 degrees, the more rapidly the motor slows. Once the desired speed has been achieved, both E_d and E_o are reversed in polarity by the same means.[4]

The manual armature reversal poses delay in most scenario's and can be unacceptable because of that, as such, to solve this issue, while increasing costs, the motor can utilize two opposing rectification circuits. This is shown in figure 6. This eliminates the need for reversing the armature field, and also allows the motor to be operated in the opposite direction as-well.[4]

While 2-Quadrant setup does allow means of braking the motor and switching motor direction, it still does not solve issues of erratic behavior at lower speeds and high reactive power consumption, as resulting of pulsating currents leading voltages.[4]

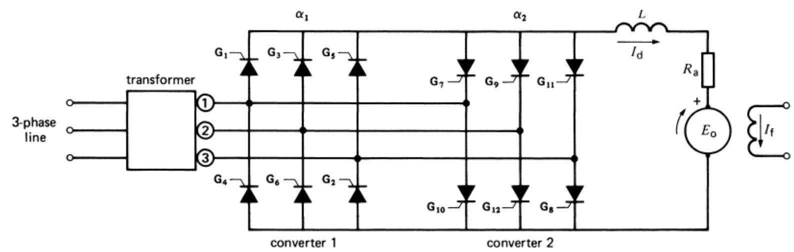

Figure 6. 2-Quadrant Control Circuit.[1]

4-Quadrant Control

Finally, we have the concept of 4-Quadrant Control. This involves utilizing two 3-Phase, 6 Pulse converters simultaneously, even during 1-Quadrant operations. This is just an extension of circuit shown in figure 6, but with two different power supplies and hence, two different circulating currents. This not only allows instantaneous control in terms of breaking, change in speed torque, but also allows current to flow uninterrupted, even though the net current flow maybe 0 at times. This removes the erratic behavior and reduces reactive power consumption. This is the most advanced, complex and expensive means of driving DC Motors.[1]

MATLAB-Simulink Model

The MATLAB-Simulink Model shown in appendix figure 7 was used to demonstrate and verify the results of our various findings in this study.

Conclusion

In this study we explored and understood in-depth the basic building-blocks of the Power Electronics in the form of the 3 Phase 6 Pulse Rectifier that are used in driving and controlling of Industrial grade DC Motors. The emphasis throughout was on separately excited DC Motors. In addition, we also learned the basic ideas behind 1-Quadrant, 2-Quadrant and 4-Quadrant Control of DC Motors and were able to connect and appreciate how the 3-Phase 6-Pulse Rectifier was extend and utilized in achieving these various levels of control for DC Motors, as well as the problems associated. Most of the findings were also supported by results from 3-Phase 6 Pulse Rectifier MATLAB-Simulink Model.

Appendix

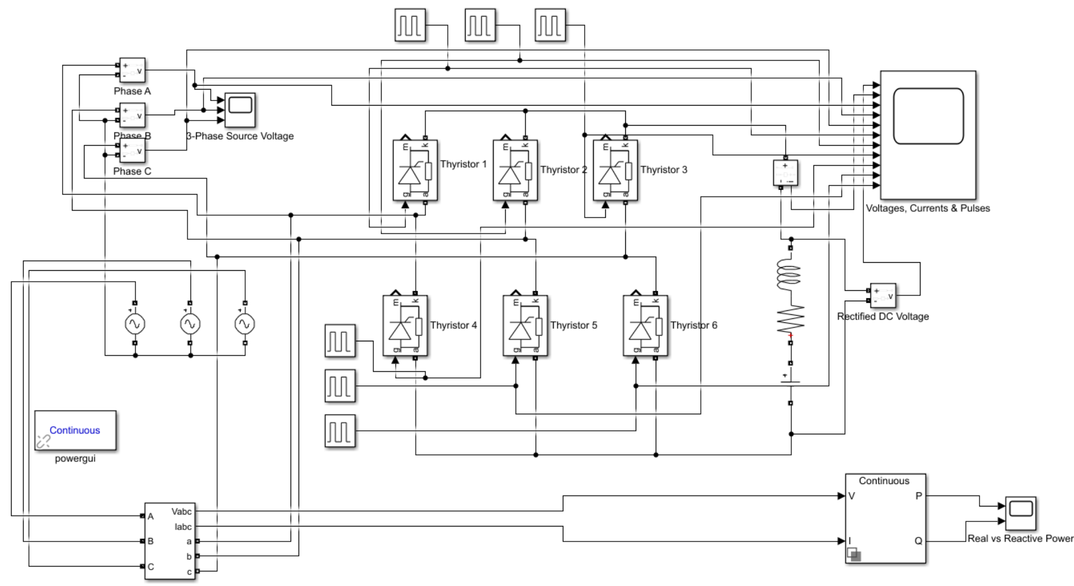

Figure 7. MATLAB-Simulink Model 3-Phase, 6 Pulse Rectifier.

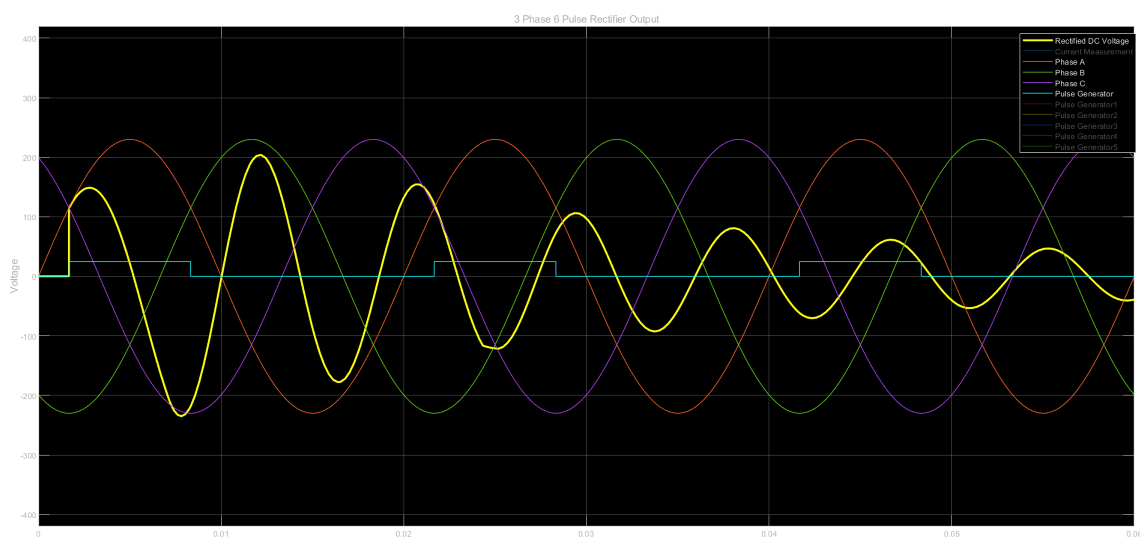

Figure 8. Click to Play! This animation show's the rectification process as successive pairs of Thyristors are given gate-pulses in a 3 Phase 6 Pulse Rectifier.

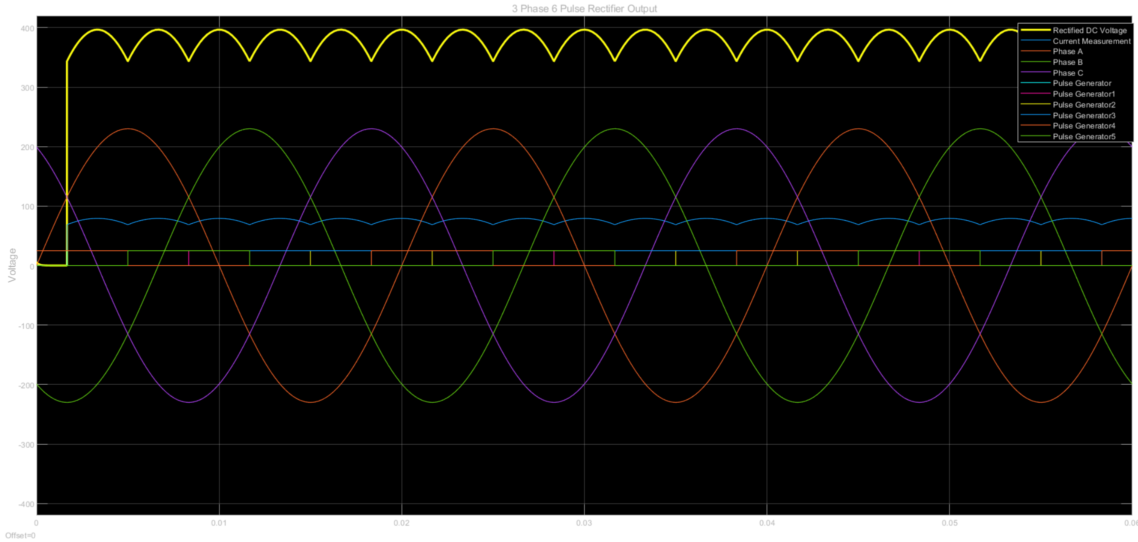

Figure 9. Click to Play! This animation show's the output voltage as the firing angle is varied from 0 to 120 ° for a resistive load in a 3 Phase 6 Pulse Rectifier.

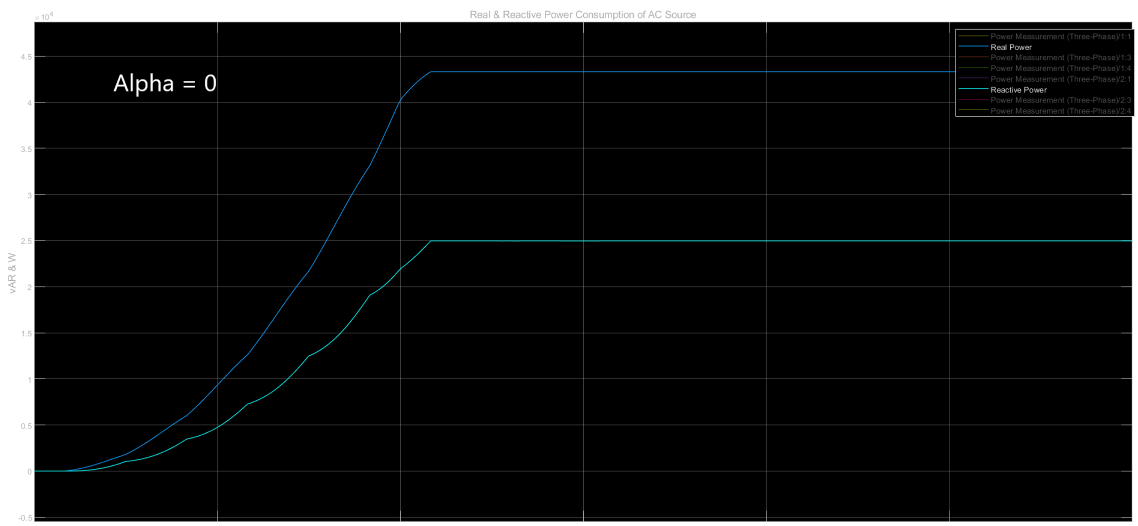

Figure 10. Click to Play! This animation show's the Real and Reactive Power stress that the 3-Phase 6 Pulse Rectifier places on the supply line as the firing angle is varied from 0 to 120 ° for a resistive load.

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