Modeling and Simulation of Three-phase ac-dc

Converter-Fed dc Drive Systems

with Uniform Pulse-Width Modulation Control

Chams-Eddine Feraga

Department of electrical Engineering

Guelma University

PO box 401, Guelma 24000, Algeria

E-mail: chferaga @yahoo.fr

Ali Yousfi

Department of electromechanical Engineering

Annaba University

PO box 12, Annaba 23000, Algeria

E-mail: yousfiali51@yahoo.fr

Abdallah Bouldjedri

Department of electrical Engineering

Annaba University

PO box 12, Annaba 23000, Algeria

E-mail: b_abj67@yahoo.fr

Abstract

A three-phase ac-dc GTO (gate turn off) thyristor converter-fed dc motor is studied employing uniform pulse-width modulation (UPWM) scheme, and verified by computer simulation. It is found to offer good performance. It offers only two-quadrant operation because of the unidirectional current conduction nature of GTO's. A four-quadrant converter that employs a single six-GTO bridge converter and four thyristors serving as a reversing switch is described. The four-quadrant dc drive employing the proposed converter and the control structure including speed and current control loop is also presented. Simulation results with a separately excited dc motor are given for steady-state and transient responses of the drive.

Keywords: Pulse Width Modulation, Ac-dc Converter, Dc drive, GTO

1. Introduction

Three-Phase ac-to-dc converters are severally applied to speed control of dc motors. They are ideal electronic actuators for DC drives because of their virtually unlimited output power and excellent controllability (Leonhard, 1997; Kazmierkowski and Tunia, 1994). The thyristor converters employing phase control have disadvantages of having harmonics in the source current and poor power factor, particularly at low-output voltages. When they are used for dc motor control, the armature current ripple increases losses, derates the motor, and causes discontinuous conduction, which increases speed regulation and slows down the transient response at light loads (Mohan and al; 2003). Forced-commutated converters with pulse width modulation (PWM) control have been developed and offer considerable performance improvement over phase-controlled converters. It makes the fundamental power factor unity the ripple of the load current and the zone of discontinuous conduction operation are reduced when compared to conventional converters (Sato and al; 1998;Wernekinck, 1991).

The increasing availability and power capability   of controlled-on and controlled-off power switching devices, such as gate turn-off thyristors (GTO's), insulated gate bipolar transistors (IGBT's), and MOS-controlled thyristors (MCT's), are expected to reinforce self-commutated ac–dc converters with PWM control strategy to replace the conventional

phase-controlled converters within the available power ratings (Zhou and Rouaud, 1999).

The flexibility to operate with variable chopping frequency is an additional merit of self-commutated PWM converters (Hamad, 1997; Trzynadlowski, 1998).

A three-phase PWM GTO converter-fed dc motor drive offers only two-quadrant operation because of the unidirectional current conduction nature of GTO's. A dual-converter is realized by employing two converters connected in antiparallel across the load, Allows operation in all four quadrants (Leonhard, 1997).

The present paper describes a four-quadrant converter that employs a single six-GTO bridge converter and four thyristors serving as a reversing switch. This allows substantial reduction in cost because GTO's are quite expensive compared to thyristors. The reduction in cost, however, is obtained at the expense of increase in losses and lower efficiency due to two extra devices in armature circuit at all times (Mohan and al; 2003; Kenjo, 1990).

We analyse the performance characteristics of an ac-dc GTO thyristor converter, employing uniform pulse width modulated (UPWM). This control strategy is employed in the normal operation of the converter either as a rectifier or an inverter. A four-quadrant dc drive employing the proposed converter and closed-loop speed control with inner current control loop is also presented. Simulation results with a separately excited dc motor are given for steady-state and transient responses of the drive. The simulation results are shown to be in good agreement with the theory.

2. Operation principle

The power circuit configuration of a three phase ac-dc converter supplying an active load such as a dc motor is showed in Figure1. The source impedance is neglected. The power semiconductor switches, operating in chopping mode, are used to vary amplitude of the average output voltage. If thyristors were employed, they must be force commutated. On the other hand, if power transistors, MOSFET's, IGBT's, IGCT'or GTO's were employed; they are self-commutated without any need for forced commutation (Mohan and al; 2003; Khan and al; 1991). Although a GTO thyristor is employed, as seen in Figure1, UPWM control strategy is used in order to control the output voltage. The Principe of this control strategy is explained in Figure 2. The carrier wave V_{cr} is compared with a variable time independent dc control voltage V_m to generate the drive signal V_g of the switching devices. The supply source is connected to the load during the interval when V_m is greater than V_{cr}. The frequency f_p of the carrier signal depends on the number of desired output voltage pulses P in one cycle of the ac supply voltage. The switching-on and switching-off times of the switching devices for the Kth pulse are given by the following expressions:

$$t_{kon} = \frac{t_p}{2}(2.k - 1 - m) \tag{1}$$

$$t_{koff} = \frac{t_p}{2}(2.k - 1 + m) \tag{2}$$

The output period of the carrier wave is given by:

$$t_p = \frac{2\pi}{P} = \frac{1}{f_p} \tag{3}$$

Where:

$$P = 6, 12, 18, 24, 30……$$
$$k = 1, 2, 3,……,P.$$

The mean output voltage of the converter is determined by the modulation index m, which for the UPWM control strategy, is varied by the control scheme in the range *(0≤ m≤1),* with the index m given by:

$$m = \frac{V_{mm}}{V_{crm}} \tag{4}$$

Where V_{mm}= peak of modulated signal, V; V_{crm}= peak of carrier signal, V.

The expressions for the corresponding modulating signal, switching-on angles α's and switching-off angles β's for the Kth pulse in a supply cycle are given by:

$$\alpha_k = \frac{\pi}{P}(2k - 1 - m) \tag{5}$$

$$\beta_k = \frac{\pi}{P}(2k - 1 + m) \tag{6}$$

2.1 Output voltage

According to Figure 2, the expression for the average output voltage V_{av} for a number P of pulses is given by (Khan and al; 1991):

$$V_{av} = \frac{3\sqrt{6}.V_s}{2.\pi} \sum_{i=1}^{P/3} \int_{\pi/6+\alpha_i}^{\pi/6+\beta_i} \sin(\omega t + \theta r) d(\omega t) \tag{7}$$

$$V_{av} = \frac{3\sqrt{6}\,V_s}{\pi} \sum_{i=1}^{P/3} \left[\cos(\alpha_i + \frac{\pi}{3}) - \cos(\beta_i + \frac{\pi}{3}) \right] \tag{8}$$

Where V_s =mean dc voltage,V; V_s =RMS amplitude of the line voltage,V; θ_r =phase angle corresponding to ith pulse, rad; ω =supply frequency, rad/s.

2.2 Output current

The expression for the armature current during the ith voltage pulse is given by:

$$i_a = I_P \sin(\omega t - \phi + \frac{\pi}{3}) - I_E$$
$$+ \left[I_{\alpha i} + \frac{E_a}{R_a} - I_P \sin(\alpha_i - \phi + \frac{\pi}{3}) \right] e^{\frac{R_a}{L_a \omega}(\alpha_i - \omega t)} \tag{9}$$

$$\alpha_i \le \omega t \le \beta_i$$

$$i_a = -\frac{E_a}{R_a} + [I_P \sin(\beta_i - \phi + \frac{\pi}{3})$$
$$+ (I_{\alpha i} + \frac{E_a}{R_a} - I_P \sin(\alpha_i - \phi + \frac{\pi}{3})) e^{\frac{R_a}{L_a \omega}(\alpha_i - \beta_i)}] e^{\frac{R_a}{L_a \omega}(\beta_i - \omega t)} \tag{10}$$

$$\beta_i \le \omega t \le \alpha_{i+1}$$

Where E_a = motor back emf, V; i_a = instantaneous armature current, A; L_a = armature circuit inductance, H; R_a = armature circuit resistance, Ω; Z = armature impedance at supply frequency=$[R^2 + (L\omega)^2]^{1/2}$, Ω; ϕ = load phase angle, rad; $I_{\alpha i}$ = armature current at α_i, A; $I_{\beta i}$ =armature current at β_i, A; I_p = peak current =$\sqrt{2}V_s/Z$, A; I_E = current component =E_a/R_a, A.

3. Four-quadrant converter

The converter power circuit with a dc motor load is shown in Figure 3. The GTO converter employs a six-GTO bridge converter. This two-quadrant GTO converter is operated with uniform PWM to produce 12 output voltage pulses during a cycle of the ac source voltage. The principle of armature reversal is shown in Figure 3 with the help of static reversing switch that consists of four reversing thyristors.

Thyristor pair (T_1, T'_1) continuously conduct for positive direction of motor current while the others are blocked. When zero current is reached, the opposite pair of thyristors (T_2, T'_2) can be fired in order to reverse the polarity of the armature current.

4. Control structure of the drive

The schematic block diagram of speed control scheme is given in Figure 4. The schematic diagram of the closed loop speed control scheme is shown in Figure 5. It employs an inner-current control loop within the speed loop. The speed controller output, which forms the current reference for the current controller, is clamped to provide a current-limiting feature.

4.1 Dc motor

The equivalent circuit of the separately excited dc motor coupled to a separately excited dc generator for the purpose of loading can be represented in a schematic form as shown in Figure 6. Assuming constant field excitation, the equations are expressed as:

$$V_a = R_a . i_a + L_a \frac{di_a}{dt} + E_a \tag{11}$$

$$m_M = J \frac{d\omega_m}{dt} + m_L \tag{12}$$

$$E_a = K_m . \omega_m \tag{13}$$

$$m_M = K_m . i_a \tag{14}$$

With m_M =Motor torque, Nm; m_L =load torque, Nm; N_m=mechanical speed, RPM; ω_m=mechanical angular velocity=$2\pi N_m/60$, rad/s; K_m=back emf constant, V/rad/s; J=moment of inertia.

Taking Laplace transform of (11) – (14) and rearranging the terms of the equations, we obtain

$$I_a = \frac{V_a(s) - K_m . \omega_m(s)}{R_a(1+T_a S)} \tag{15}$$

$$\omega_m = \frac{K_m . I_a(s) - m_L(s)}{J S} \tag{16}$$

$$\omega_m = \frac{m_M(s) - m_L(s)}{J S} \tag{17}$$

where S is the Laplace operator.

The dynamic system, described by equations (15), (16), (17), is represented by a block diagram in Figure 7. As a constant field dc generator connected to a fixed resistance forms the load on the motor shaft, the load torque varies linearly with the speed. The equation is:

$$m_L = B . \omega_m \tag{18}$$

4.2 Converter

The secondary voltage of the power transformer is chosen in such a way that for the control voltage V_c=0.9 V_{cmax}, the converter voltage is equal to the rated voltage of the dc motor.

The control voltage varies from - 5 to + 5V. Gain K_t of the converter (including the firing circuit) is given as the ratio of the maximum value of desired output voltage to the change in control voltage V_c required to vary the output voltage from *0* to V_{cmax}. The time delay of the converter is approximated by first-order time constant T_t which is equal to half the interval between two consecutive voltage pulses (Leonhard, 1997,Khan and al;1991).

Thus,

$$T_t = \frac{1}{2} . \frac{20}{6} ms \qquad for \qquad P = 6$$

And

$$T_t = \frac{1}{2} . \frac{20}{12} ms \qquad for \quad P = 12$$

The transfer function of the converter can be written as:

$$\frac{V_a(s)}{V_c(s)} = \frac{K_t}{1+T_t S} \tag{19}$$

4.3 Current transducer

A signal proportional to the armature current is obtained by using a small resistance in series with the armature circuit. The feedback signal derived from the current transducer is applied to an RC filter with a time constant T_2 in order to reduce the ripple in the current signal. Thus, the transfer function of the current transducer with the filter is written as:

$$\frac{I_m(s)}{I_a(s)} = \frac{K_2}{1+T_2 S} \tag{20}$$

4.4 Speed transducer

A tacho-generator is used to get the speed signal. Since a 5V dc signal corresponds to the rated speed *(1500 r/min).*An RC filter with a time constant T_1 is used to smooth out the spikes in the speed signal. The transfer function of the speed transducer with the filter is given as:

$$\frac{V_m(s)}{\omega_m(s)} = \frac{K_1}{1+T_1 S} \tag{21}$$

5. Simulated Results and Discussions

The parameters of the used machine model are given in Table 1.The source voltage; the motor armature voltage and current waveforms for motoring and regenerating (for rectification and inversion) operation, are shown in Figure 8 and Figure 9 respectively. The waveforms of the developed torque and the motor speed for a different number of pulses *P* *(P=6 and P=12)* are shown in Figure 10, where the load is applied at *t=1s*. The ripples in the developed torque were

observed.

There is an improvement in performance with an increase in the pulse number. Four-quadrant drive ability is demonstrated in Figure 11 and Figure 12. The former shows the speed response for a speed reversal command from *+1500* to *-1500 rpm*. As the speed reversal is initiated, the armature current quickly reverses through the static reversing switch. The motor decelerates to standstill as the converter operates as an inverter feeding power back the ac supply. The motor is then accelerating fast in the reverse direction and the speed settles down to the desired value.

Figure 12 shows the speed response for control voltage varying from -5 to +5v, with a load torque m_L=constant. The armature current reverses though the reversing switch the motor is decelerated quickly. When desired speed is reached, the current is again set back in previous direction (corresponding to the operation in a four quadrant drive).

6. Conclusion

The study of pulse width modulation scheme for an ac-dc PWM converter shows that the uniform pulse width modulation scheme offers good performance. Simulation results show that the control strategy can be applied to both rectifying and regenerating modes of operation. A four-quadrant dc drive employing the proposed converter and closed-loop speed control with inner current control loop has been described and verified by computer simulation. The simulation results are shown to be in good agreement with the theoretical calculations.

References

Hamed, S.A., (1997). Performance Evaluation of Three-Phase Variable –Speed DC Drive Systems with Uniform PWM Control. *IEEE, Trans. on Power Electronics*,12: 228-242.

Kazmierkowski M. P., & H. Tunia, (1994). *Automatic Control of Converter-Fed Drives*. Elsevier Amsterdam.

Kenjo, T., (1990). *Electric Motors and Their Controls: An Introduction*. Oxford Science Oxford UK.

Khan, B.H., Doradla, & G. K. Dubey, (1991). A Three Phase AC-DC GTO Converter Employing Equal Pulse Width Modulation (EPWM). *IEEE Trans. on Industry Applications*, 27: 370–379.

Khan, B.H., S. R. Doradla, & G. K. Dubey, (1991). A New Simultaneous Gating GTO Dual Converter- fed DC Motor Drive without Circulating Current. *IEEE Trans. on Industry Applications*, 27: 560-566.

Leonhard, W., (1997). *Control of Electrical Drives*. Spinger Verlag Berlin Heidelberg.

Mohan, N., T.M. Undeland, & W.P. Robbins, (2003). *Power Electronics: Converters Applications and Design*. Wiley & sons NewYork.

Sato, Y., T.Ishizuka, K. Nezu & T. Kataoka, (1998). A New Control Strategy for Voltage- Type PWM Rectifiers to Realize Zero Steady-State Control Error in Input Current. *IEEE Trans. on Power Electronics*, 34: 480 -486.

Trzynadlowski, A. M.,(1998). *Introduction to Modern Power Electronics*. John Wiley New York.

Wernekinck, E., A.Kawamura, & R.Hoft, (1991). A High Frequency AC/DC Converter with Unity Power Factor and Minimum Harmonic Distortion. *IEEE Trans. on Power Electronics*, 6: 364-371.

Zhou, D., & D. Rouaud, (1999). Regulation and design issues of a PWM three-phase rectifier. *The 25th Annual Conference of the IEEE IECON '99* , San Jose, California, USA, November 29 – December 03, 1: 485-489.

Table 1. Separately excited DC machine data

Components	Rating values
Power	*P =3hp*
Voltage	*V =220V*
Current	*I =11.6A*
Speed	N_m *=1500r/min*
Armature resistance	R_a *= 3.1Ω*
Electrical time constant of the armature circuit	T_a *= 7.74 ms*
Moment of inertia	$J = 0.025kg.m^2$
Coefficient of viscous friction	*B = 0.089Nm/rad/s*
Mechanical time constant	T_m*= 4.1 ms*

Figure 1. Three-phase ac-dc converter

Figure 2. Principle of UPWM control strategy

Figure 3. Four-quadrant operation of a DC drive

Figure 4. General schematic of closed-loop speed control

Figure 5. Control structure of a drive including speed and current control loop

Figure 6. Equivalent circuit of dc motor+load system. Figure 7. Block diagram of motor+load system

(a)

(b)

Figure 8. Simulated waveforms of output voltage and load current through UPWM GTO converter

(a) for motoring operation *(P=6, m=0.8)*

(b) for regenerating operation*(P=6,m=0.8)*

(a)

(b)

Figure 9. Simulated waveforms of output voltage and load current through UPWM GTO converter

(a) for motoring operation *(P=12,m=0.8)*

(b) for regenerating operation *(P=12,m=0.8)*

Figure 10. Response of torque and speed of UPWM ac-dc converter-fed dc motor

(a)   when   *(P=6, m=0.6)*

(b)   when   *(P=12, m=0.6)*

Figure 11. Speed and torque responses for reversal of speed command

From *1500* to *-1500 r/min* of closed loop scheme When $m_L = B.\omega$

Figure 12. Speed and torque responses for reversal of speed command

From *1500* to *-1500 r/min* of closed loop scheme When m_L =*constant*