

Design of a Reversible Soft-Starter for an Induction Motor

M. Rabiee
Eastern Kentucky University

Abstract:

This paper describes a student project that studies the design of a Reversible Soft-Starter for an Alternating Current (AC) Induction Motor. Alternating Current (AC) converters are used as Motor Starters / Reversing for large AC induction motors. Starting a large motor that utilizes an AC Converter will eliminate the need to draw a large amount of current during the transient period, thereby insuring that starting a large motor will not disturb adjacent power lines.

This student project designed a 50 Horse Power (HP) variable-speed motor starter. First, the equivalent circuit parameters of a 50-HP induction motor were used to calculate and size the Silicon Controlled Rectifiers (SCRs) utilized within the converter. The converter has ten (10) main SCRs. The students with the author's guide then used the thermal equivalent circuit to solve the heat transfer problem, and to size the correct heat sinks for the SCRs. In the third section of the paper, we will explain the effect of current and voltage variations (dv/dt , and di/dt) on the SCRs. Then, we will design the "RC Snubber" circuits to protect the SCRs against the voltage (dv/dt) variation. Finally, we will devise a control routine in order to provide the appropriate gate current firing of the SCRs.

The specifications state that pushing the "STARTER" will automatically bring the command voltage (V_K) up as a ramp function, it will take fifteen (15) seconds for the command signal to reach 15 V value. This signal is subtracted from a constant 15 V DC voltage. We have called the resulting signal the Error Signal, V_E . The error signal is used to calculate the Gate to Cathode voltage value of each SCR. When the gate to cathode voltage appears across one forward biased SCR, it will start to conduct, and there will be low voltage on the terminal of the motor. The terminal voltage increases as the command signal (V_K) increases until the motor reaches its rated speed. At that point, the motor has a constant Root Mean Square (RMS) voltage value across its terminals. For reversing, we push another button labeled "REVERSE". Once the reverse push button is pressed, the command signal decreases until it is zero when the motor has stopped. Now the system will wait for one (1) second to insure that no current is passing through the coils. Since the frequency is 60 Hz, a one (1) second delay is a sufficient delay time. The controller will change the phase sequence and automatically push the motor starter. The motor will have a reversed direction of rotation. In this paper, we will also explain the way system controls SCR gate currents. There are several textbooks available which can be used for reviewing and learning the design steps [1, 2, 3].

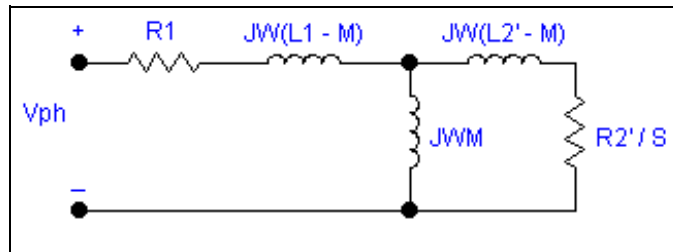
Design specifications:

The induction motor parameters for the design are listed below.

Source Line Voltage, $V_L = 480V$

Source Frequency, $f = 60 \text{ HZ}$
 Motor Horse Power Rating, $P_M = 50\text{HP}$ @ 480 V, and rated speed of 1705 RPM
 Per-Phase Stator Coil Resistance, $R_1 = 0.09078 \Omega$
 Per-Phase Rotor Coil Resistance Reflected to the Stator, $R'_2 = 0.23791 \Omega$
 Per-Phase Stator Coil Self Inductance, $L_1 = 0.037043 \text{ H}$
 Per-Phase Rotor Coil Self Inductance Reflected to the Stator, $L'_2 = 0.037043 \text{ H}$
 Per-Phase Mutual Inductance between the Stator and Rotor Coils, $M = 0.03621 \text{ H}$

Figure 1 displays steady-state an induction motor.



the per-phase, equivalent circuit of

Figure 1. Equivalent Circuit of An Induction Motor

The rated speed of 1705 RPM requires a four-pole induction motor with a synchronous speed of 1800 RPM.

$$\text{Angular Velocity, } \omega_s = 120f / p = (120 * 60) / 4 = 1800 \text{ RPM}$$

Thus the slip, S at 1705 rpm is calculated as follows,

$$\text{Slip, } S = (\omega_s - \omega_m) / \omega_s = (1800 - 1705) / 1800 = 0.0527778$$

Therefore,

$$R'_2 / S = 0.23791 / 0.0527778 = 4.50777 \Omega$$

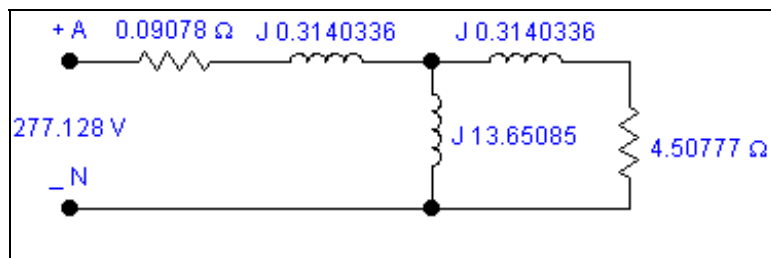
$$X_1 = X'_2 = j \omega (L_1 - M) = j \omega (L'_2 - M) = j (2\pi * 60)(0.037043 - 0.03621) = j 0.3140336 \Omega$$

$$X_m = j \omega M = j (2\pi * 60)(0.03621) = j 13.6508 \Omega$$

$$V_{ph} = 480 / \sqrt{3} = 277.128 \text{ V}$$

The SCR Process:

Figure 2 per-phase, induction motor circuit at the 1705 RPM.



Selection

displays the steady-state equivalent rated speed of

Figure 2. Equivalent Circuit at Rated Speed

Let us calculate the input impedance of the circuit displayed in figure 2.

The referred rotor coil resistance and self-reactance are in series, and their equivalent value is in parallel with the mutual reactance. Therefore, calculate their equivalent value as listed below.

$$\begin{aligned}
 & j 0.3140336 + 4.50777 = 4.51867 \Omega @ 3.985^\circ \text{ phase angle} \\
 & (4.51867 \Omega @ 3.985^\circ) || (13.65085 \Omega @ 90^\circ) \\
 & = [(4.51867 @ 3.985^\circ) * (13.65085 @ 90^\circ)] / (j0.3140336 + 4.50777 + j13.65085) \\
 & = 4.203324 \Omega @ 21.875^\circ = 3.90068 + j 1.566087
 \end{aligned}$$

The above equivalent impedance is in series with the starter resistance and self reactance values. Therefore, the per-phase input impedance is calculated as listed below.

$$\begin{aligned}
 Z' &= (0.09078 + j 0.3140336) + (3.90068 + j 1.566087) \\
 Z' &= 3.99146 + j 1.8801206 = 4.41209771 \Omega @ 25.22^\circ
 \end{aligned}$$

The per-phase current and voltage phase shift, peak line voltage, and peak phase voltage are listed below.

$$\begin{aligned}
 \Phi &= 25.22^\circ \\
 V_{\text{Peak - Line}} &= \sqrt{2} V_{\text{Line}} = \sqrt{2} * 480 = 679 \text{ V} \\
 V_{\text{Peak - Phase}} &= V_{\text{Peak - Line}} / \sqrt{3} = (\sqrt{2} * 480) / \sqrt{3} = 392 \text{ V}
 \end{aligned}$$

We assume that the three phase source voltages and motor coils are Y-connected systems. We then can calculate the Base Current I_{Base} , and the Phase Current I_1 which is the same as the Line current as listed below.

$$\begin{aligned}
 |I_{\text{Base}}| &= V_{\text{Peak - Line}} / |z| = (\sqrt{2} * 480) / (\sqrt{3} * |z|) = (\sqrt{2} * 480) / (\sqrt{3} * 4.4120977) \\
 &= 88.828123 \text{ A} \\
 |I_1| &= (480 / \sqrt{3}) / 4.4120977 = 277.128 / 4.4120977 = 62.81094 \text{ A}
 \end{aligned}$$

Normalized Root Mean Square (RMS) current through one line is listed below.

$$|I_R| = |I_1| / |I_{\text{Base}}| = 0.707107$$

Since there are two SCRs in one line, the total RMS current squared, equals the individual RMS current squares.

$$I_R^2 = I_{R1}^2 + I_{R2}^2 = I_{R1}^2 + I_{R1}^2 = 2 * I_{R1}^2$$

Therefore, to get the Normalized current through one SCR we must divide the normalized RMS line current by $\sqrt{2}$. Normalized Root Mean Square (RMS) current through one SCR, $I_{RN} = I_R / \sqrt{2} = 0.5000$

The RMS current (I_{RN}) represents a DC value that could generate the same amount of power dissipation. The average current (I_N) represents the average value of the current through SCR in any direction. For a pure resistive load, we can assume that the input voltage and the input current do not have any phase shift. Therefore, the total power transferred through one SCR in terms of average current can be calculated as listed below.

$$V_{RN} * I_{RN} = 2 * I_N * V_N \quad \text{or} \quad I_{RN}^2 * R = 2 * I_N^2 * R \quad \text{or} \quad I_{RN}^2 = 2 * I_N^2$$

Hence, Normalized **average** current through one SCR is $I_N = I_{RN} / \sqrt{2} = 0.3535$. Average current is calculated as listed below.

$$I_{Average} = (I_N)(I_{Base}) = (0.3535)(88.82813) = 31.40 \text{ A}$$

Let us assume that there could be a 25% overload in the system then, $I = 1.25 * 31.40 = 39.25 \text{ A}$. The line voltage is 480V, but we allow an experience factor of 2.5 due to voltage spikes. Consequently, the SCR current and voltage specifications are as listed below.

$$I = 39.25 \text{ A}$$

$$V = 1200 \text{ V} = 2.5 * 480 \text{ V}$$

Looking through the Silicon Controlled Rectifier Data Book [4], we will select the 2N4377 SCR for this particular Voltage Converter system.

Heat Sink Selection:

Now, let us calculate the required parameters for finding suitable heat sinks for these SCR's. First we need to specify a single SCR's power dissipation capacity from the plot of maximum power dissipation versus average forward current [4]. Figure 3 displays that the maximum SCR conduction angle is 150°. Conduction angle refers to the duration when the SCR is forward biased.

Figure 4 display the manufacturer's characteristic curves for the SCR. We interpolate from the "Maximum Power Dissipation" curve that $P_{\text{Dissipation}}$ is equal to 60 W.

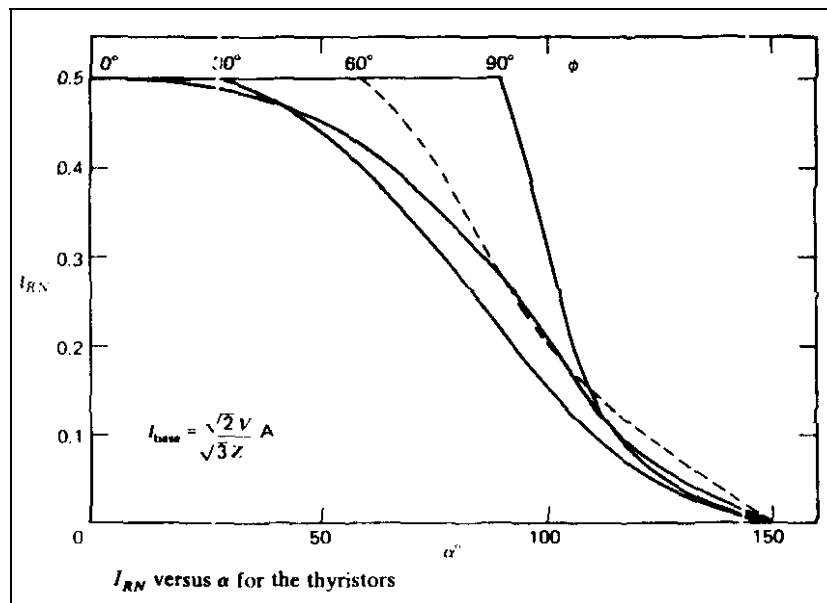


Figure 3. Average SCR Current Versus SCR Conduction Angle

From the plot of average forward current versus case temperature (See Figure 4), we find that the Case Temperature, T_C is 115 °C. Also, from the data sheet (See Figure 4) we see that the Case to Sink Coefficient, θ_{CS} is 0.12 °C/W for three seconds thermal transient time.

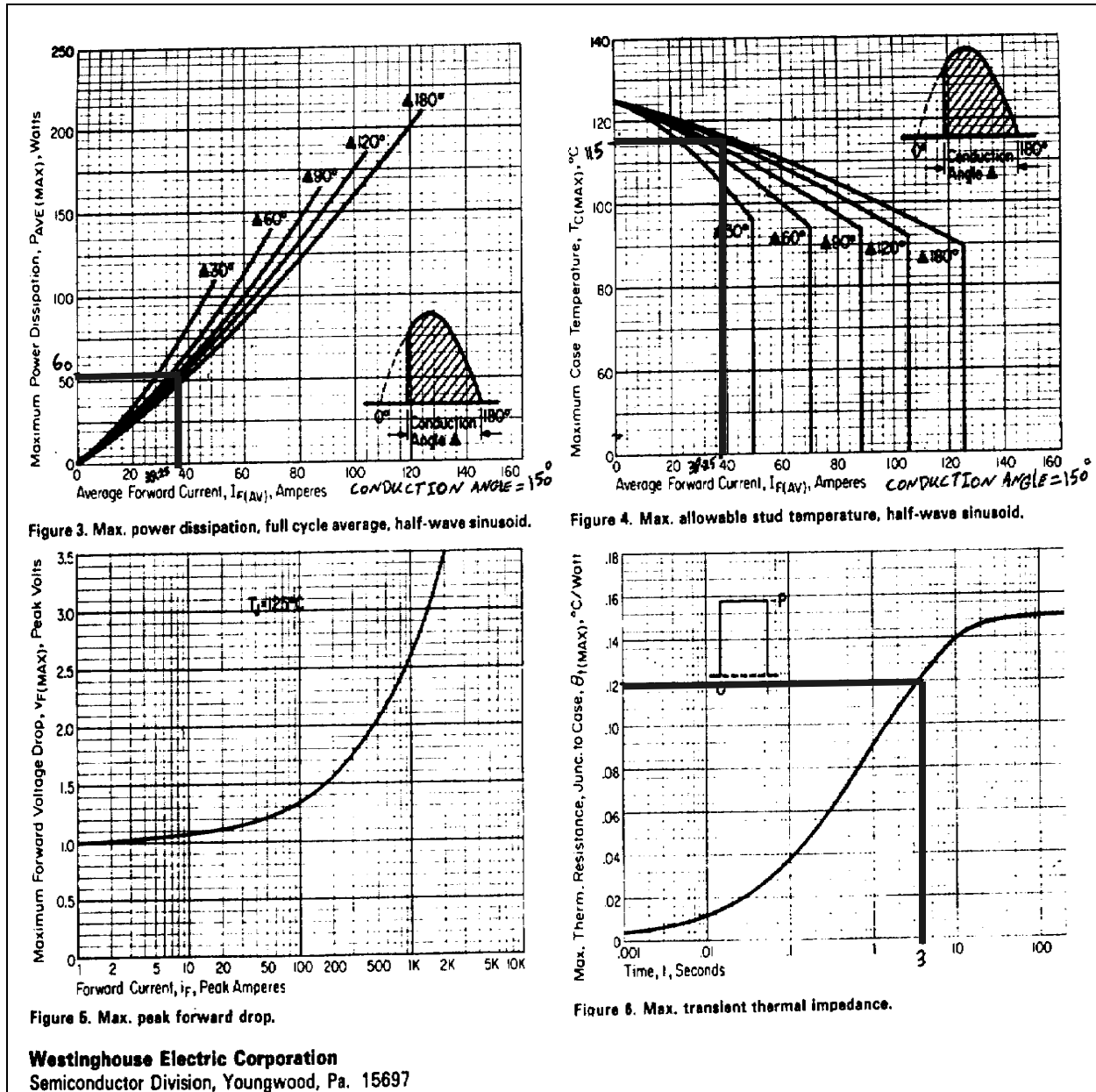


Figure 4. SCR characteristic Curves.

Figure 5 displays the analogous heat transfer equivalent circuit. This circuit displays the temperatures and coefficients of power dissipation in terms of generated heat in each SCR and Heat Sink surfaces.

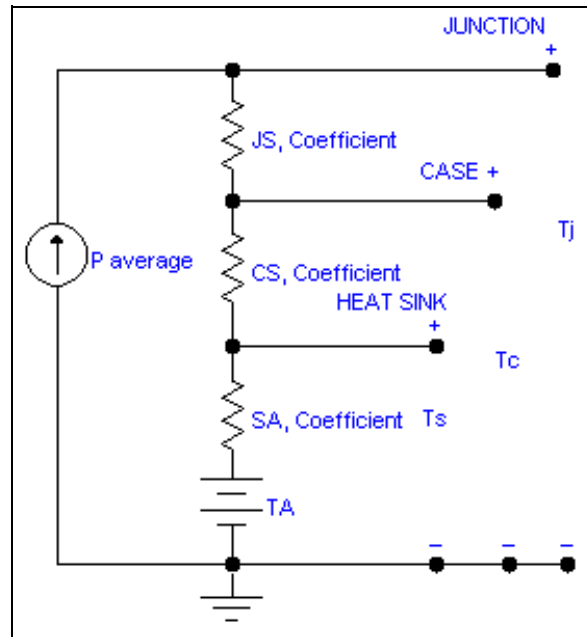


Figure 5. Heat Dissipation equivalent Circuit

The thermal parameters following.

are defined in the

T_J = SCR Junction Temperature, °C

T_C = Case Temperature, °C

T_A = Ambient or Room Temperature, °C

T_S = Heat Sink Temperature, °C

θ_{JC} = Junction to Case Temperature Coefficient, °C/W

θ_{CS} = Case to Heat Sink Temperature Coefficient, °C/W

θ_{SA} = Heat Sink to Ambient Temperature Coefficient, °C/W

Using the above mentioned temperatures, we can calculate the ambient to heat sink temperature coefficient as stated below.

$$T_S = T_C - P_{\text{average}} * \theta_{CS}$$

$$T_S = 115 - (60 \text{ W})(0.12 \text{ °C / W}) = 107.8 \text{ °C}$$

$$\Delta T = T_S - T_A = 107.8 - 50 = 57.8 \text{ °C}$$

$$\theta_{SA} = \Delta T / P_{\text{average}} = 57.8 / 60 = 0.9633 \text{ °C/W}$$

For the value $\theta_{SA} = 0.9633 \text{ °C/W}$, we utilize a heat sink manual to select the model **421** heat sink with a required air velocity of approximately **98 FPM** (Feet Per Minute). Then we compare the dimension of the SCR's base and the dimension of the mounting surface on the heat sink to verify that the SCR can fit on the heat sink.

We note that the selected heat sink, requires 98 FPM of air velocity. We next select a case that can house the heat sinks with mounted SCRs, and also the fan, fuse box, snubber circuits, and

the control box. The housing unit's dimensions are selected to have Height, Width and Length measurement of 14" x 12" x 24" respectively. Therefore, the case has a volume of $(14" \times 12" \times 24") / (12 \times 12 \times 12 \text{ cubic inch} / \text{ft}^3) = 2.33 \text{ ft}^3$. The heat sink air velocity of 98 F.P.M., and the housing case volume of 2.33 ft^3 will result in a minimum air flow capacity of $2.33 \text{ ft}^3 \times 98 \text{ FPM} = 228.35 \text{ Cubic Feet Per Minute (CFM)}$. We therefore select a fan with an air flow capacity of 250 CFM.

Fuse and Snubber Circuits:

In order to find the fuse rating, we read from the SCR's data sheet that $I^2 t = 10,700 \text{ A}^2 \text{ sec}$. We have also calculated that under overload condition, the RMS current through one SCR is 39.25 Ampere. With two SCRs on each line the average current through one line is 78.5 Ampere, or approximately 80 Ampere. Therefore we select three fuses rated for 480 V, 80 A, and $10,700 \text{ A}^2 \text{ sec}$.

Before we draw the schematic diagram of the converter circuit, let us discuss protection methods against the rate of current and voltage changes (di/dt and dv/dt). As for the di/dt protection of the SCR's, the motor winding has sufficient inductance to take care of rapid current changes. This is done because, current through the inductor cannot change instantaneously. For dv/dt protection we need similar to the one displayed

“RC Snubber” circuits in Figure 6.

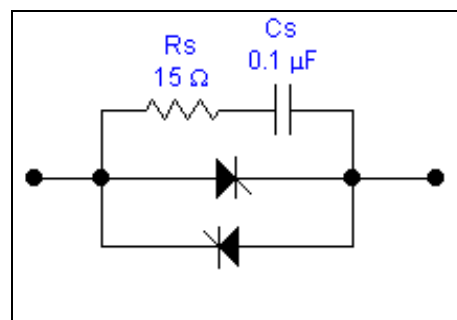


Figure 6. RC Snubber Circuit

The RC Snubbers are utilized because, the voltage across a capacitor can not change instantaneously. Since we have ten SCR's, we should have five “snubber” networks (i.e., one for each pair of SCR's). The reason we have ten SCR's instead of six SCRs is that, when reversing the direction of the rotation for the motor, we must use two separate pairs of SCRs, so that the phase sequence of the current going into the motor can be changed.

Therefore, for this design we select $1\mu\text{F}$ capacitors which have cylindrical shapes with a 2" diameter and a 3" height. These dimensions are based on the capacitor voltage and current ratings. We also selected fifteen ohms resistors.

SCR Gate Current Control:

The schematic diagram listed in Figure 7 displays a variable speed drive with reversing option. We have placed Q1 & Q4, Q5 & Q2, Q3 & Q6, Q1* & Q4*, and Q3* & Q6* next to each other. These SCR pairs use the same snubber circuits and cannot be turned on simultaneously. We will now discuss the gate current firing sequence of the SCR pairs.

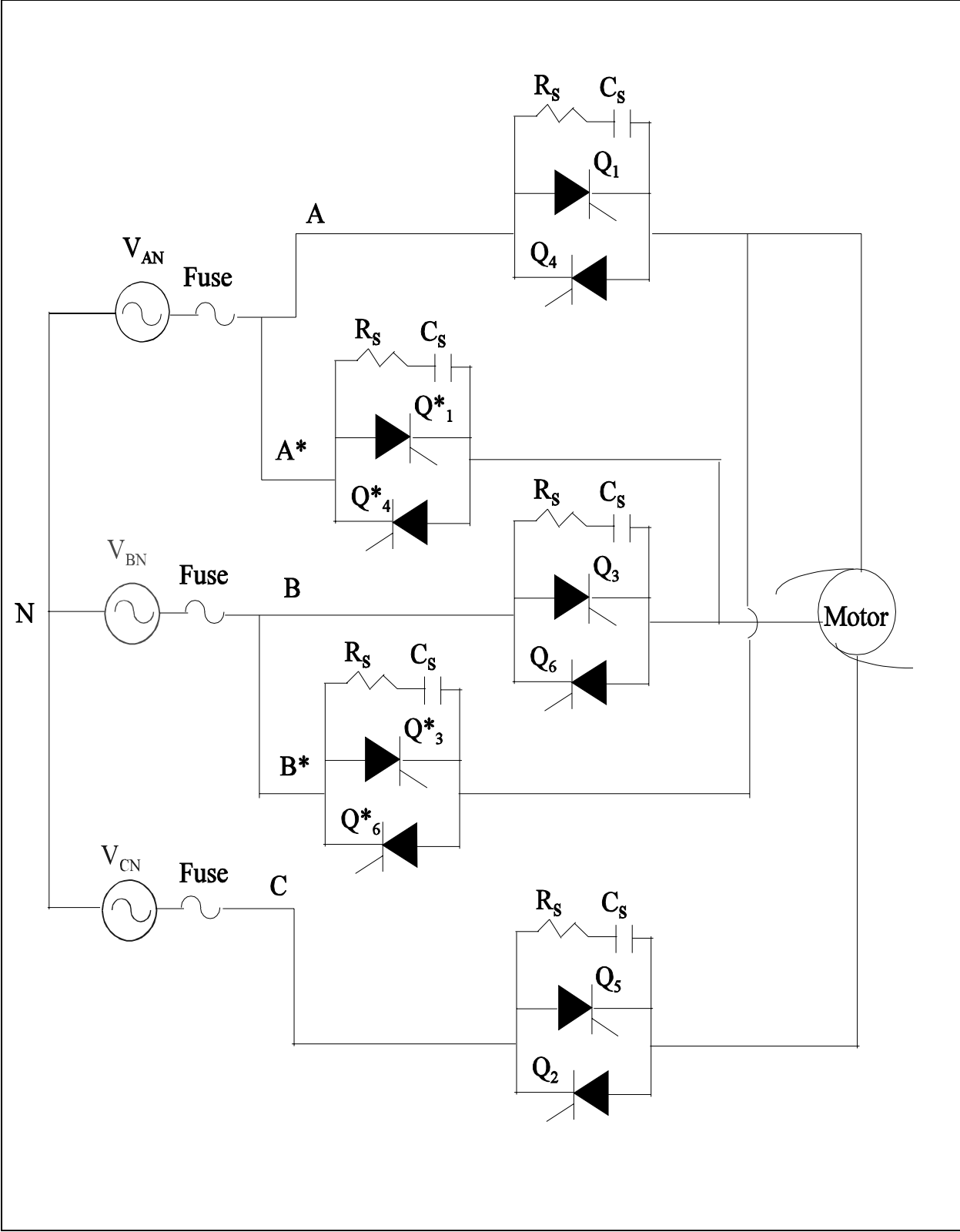


Figure 7. Schematic Diagram of the Variable Voltage Drive.

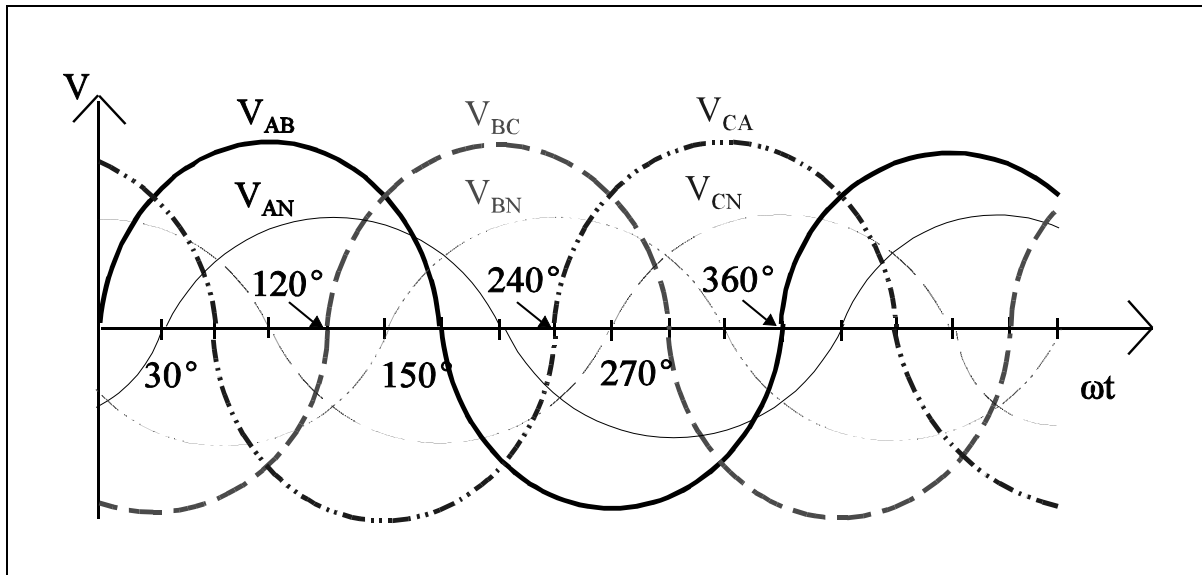


Figure 8. Line and Phase Voltage Waveforms.

Figure 8 displays Line and Phase voltage waveforms of a three-phase system. Line voltages V_{AB} , V_{BC} , and V_{CA} are 120° out phase. Phase voltages V_{AN} , V_{BN} , and V_{CN} are also 120° out phase. In Y-connected system, the phase voltages and their associate line voltages are 30° out of phase.

The following list describes the gate current readiness requirement of SCRs. We will start at the 30° angle, because in a Y-connected system the phase voltages lag the line voltages by 30° . Also, for a pure resistive Y-connected load, phase voltages and line voltages do not have any phase shift.

- When V_{AB} is positive, it tends to drive Q_1 & Q_6 , or Q_1^* & Q_6^* . Therefore, at $\omega t = 30^\circ$ there should be a current pulse ready to send into the G_1 & G_6 , or G_1^* & G_6^* gates.
- When V_{BC} is positive, it tends to drive Q_3 & Q_2 . Therefore, at $\omega t = 120^\circ$ there should be a current pulse ready to send into the G_3 & G_2 gates.
- When V_{CA} is positive, it tends to drive Q_5 & Q_4 . Therefore, at $\omega t = 30^\circ$ there should be a current pulse ready to send into the G_5 & G_4 gates.
- When V_{AB} is negative, it tends to drive Q_4 & Q_3 , or Q_4^* & Q_3^* . Therefore, at $\omega t = 180^\circ$ there should be a current pulse ready to send into the G_4 & G_3 , or G_4^* & G_3^* gates.
- When V_{BC} is negative, it tends to drive Q_6 & Q_5 . Therefore, at $\omega t = 30^\circ$ there should be a current pulse ready to send into the G_6 & G_5 gates.
- When V_{CA} is negative, it tends to drive Q_2 & Q_1 . Therefore, at $\omega t = 60^\circ$ there should be a current pulse ready to send into the G_2 & G_1 gates.

Fig 9
 plots
 the
 current
 of
 the
 first
 SCR,
 which
 is
 labeled I_{G1} .

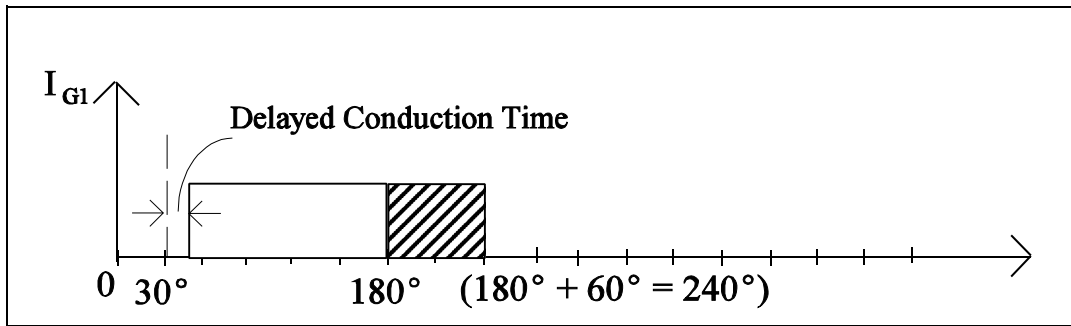


Figure 9. Gate Current for Q_1 , Using the Reference Line Voltage V_{AB}

ure
 dis
 ys
 gate
 ent
 the
 SC
 whi
 is

There are two observations to be made:

- 1) When V_{AB} is positive and tends to drive Q_1 , there should be a gate current available which has an α° delayed time. This delay time depends on the amount of average voltage we want the converter to provide (i.e., for greater α° , the RMS voltage available is less).
- 2) If we want continuous conduction we should have current in the gate of Q_1 when V_{CA} is negative and tends to drive Q_1 which is from 180° to $180^\circ + 60^\circ = 240^\circ$. Therefore, we must always have a gate current during the 180° to 240° bandwidth.

So far we have selected the line voltage V_{AB} as a reference voltage. Subsequently, let us select the phase voltage V_{AN} as the reference voltage. Figure 10 displays the SCR gate current with reference to phase voltage. Notice that we can vary the time the gate current is available from 0° to 180° but we must have the gate current available from 180° to $180^\circ + 60^\circ = 240^\circ$.

Figure 11 displays the gate currents for all the SCRs in the Voltage Converter system. The assumption has been made that the current firing angle is zero (i.e., $\alpha = 0^\circ$).

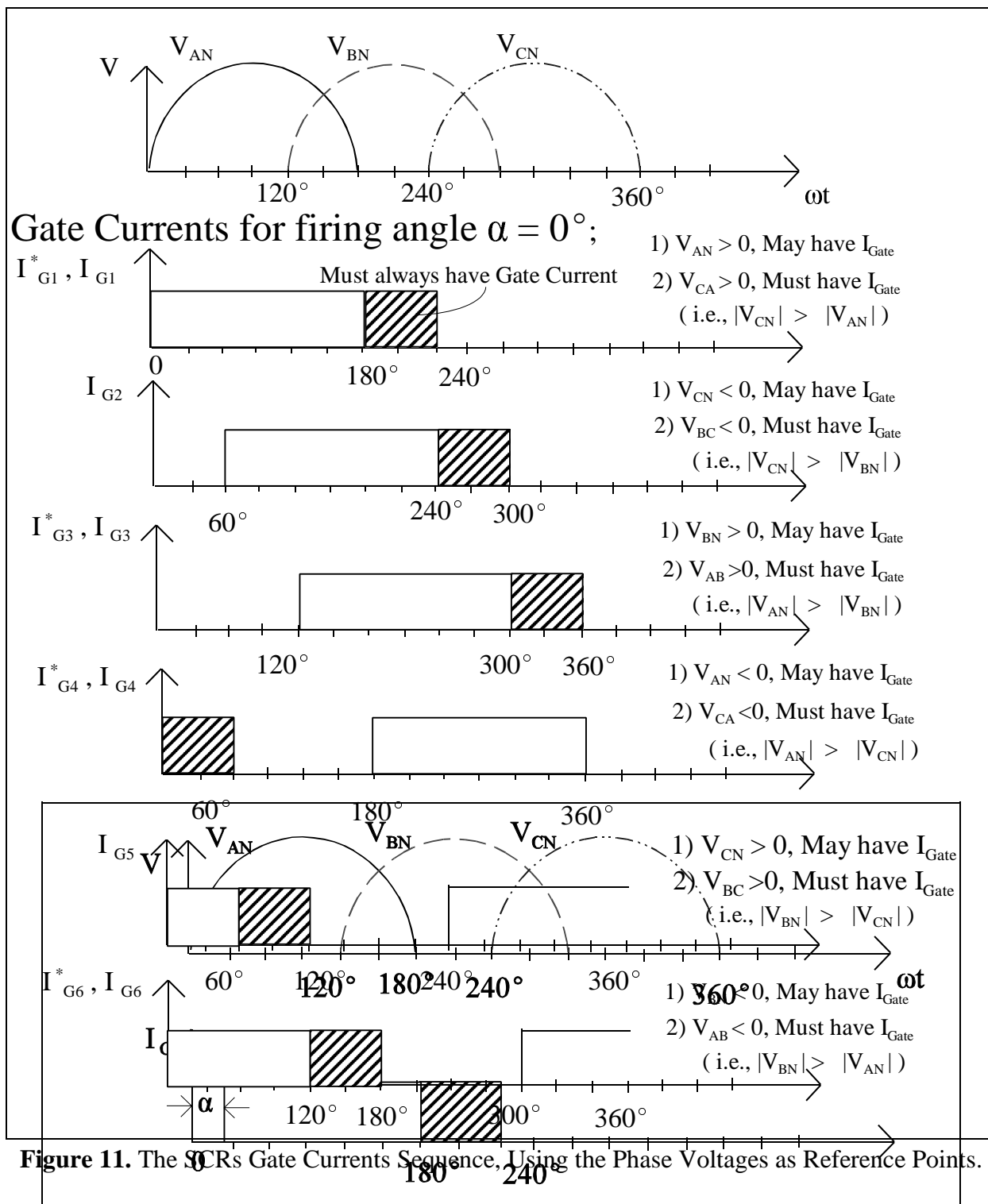


Figure 10 Gate Current I_{G1} , Using the Reference Phase Voltage V_{AN}

Analog and digital electronic circuits can be utilized to implement the aforementioned control regime. The author's intention is to present the electronic control circuit of this Voltage Converter Motor Drive in a future paper.

Conclusion:

This project was used to familiarize students with power conditioning drive systems. The project was part of an assignment for a senior level class. Throughout the course students were encouraged to utilize the World Wide Web (WWW) in order to learn about different manufacturer's product specification manuals. Also, to emphasize the concept of a design team situation, students worked in groups to complete their projects.

References:

1. Rotating Electric Machinery and Transformers Technology, Fourth Edition, Donald V. Richardson / Arthur J. Caisse Jr., 1996, Prentice-Hall Inc., Englewood Cliffs, NJ 07632.
2. Introduction to Power electronics, Daniel W. Hart, 1997, Prentice-Hall Inc., Englewood Cliffs, NJ 07632.
3. Power Electronics for Technology, Ashfaq Ahmed, 1998, Prentice-Hall Inc., Englewood Cliffs, NJ 07632.
4. Thyristor / Silicon Controlled Rectifiers, Westinghouse Electric Corporation, Semiconductor Division, Young wood, PA 15697.

MASSOUD RABIEE received his Ph.D. in Electrical Engineering, from University of Kentucky, in 1987. He is presently a professor at Eastern Kentucky University. Dr. Rabiee is a registered professional Engineer in the State of Kentucky, and a member of IEEE, ASEE, and NAIT.