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"AC Adjustable Voltage vs
Adj. Freq. Control - Bridges"

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AC Adjustable Voltage
vs
Adjustable Frequency Control
for
Movable Bridge Applications

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Introduction

For movable bridge applications, solid state AC motor controllers provide improved performance over the older stepped contactor and "Drum" controllers and the obsolete saturable reactor and magnetic amplifier systems. Solid state controls provide smooth accelerations, controlled torque levels, and automatic compensation for overhauling loads. Solid state controls also interface easily with controlling relay logic or programmable controllers.

Solid state speed control of AC induction motors can be obtained in two ways. First, by simply controlling the fixed frequency voltage applied to the motor, the motor's torque characteristic can be altered, and second, by controlling the applied voltage and frequency, the motor's synchronous speed can be changed. These methods result in two distinct types of AC adjustable speed controllers, the SCR Adjustable Voltage Controller and the Adjustable Voltage Adjustable Frequency Controller more commonly referred to as an Adjustable Frequency Inverter.

AC Adjustable Voltage Control

The AC adjustable voltage controller uses SCRs connected in inverse parallel in each phase supplying the motor. See figure 1. The SCRs control the average voltage applied to the motor on a cycle by cycle basis by means of phase angle control. With this method, the SCR will block all voltage up to the time of firing or gating and then apply the remaining portion of the half cycle to the motor. The average voltage supplied to the motor can thus be adjusted by controlling the phase or firing angle signal gating the SCRs. This method produces a controllable voltage source of fixed frequency. See figure 2.

AC SCR adjustable voltage controllers operate an induction motor in one of three modes depending upon mechanical loading and changing speed or direction commands. See figure 3. The primary operational mode will be driving or motoring where the motor is doing work and delivering power to the load. A span raise operation would be an example of a driving or motoring operation. When work is done by the load on the motor, such as slowing down a load moving at a greater speed, or lowering an overhauling load, two choices are available depending upon the speed of operation desired. If an overhauling load is to be lowered at full motor speed, full lowering voltage can be applied to the motor and the motor will function as an induction generator returning the recovered energy to the power system through the SCR controller. This mode of operation is termed regeneration, and with SCR adjustable voltage controllers, is only possible at speeds equal to or greater than the motor's 60 Hz synchronous speed. If an overhauling load is to be lowered at less than motor synchronous speed, counter-torque operation is required. In this mode, the motor produces opposing or counter torque to control the load. The SCR controller accomplishes this action by providing a limited opposing voltage while monitoring the speed of the load and motor. Counter-torque operation may also be used during periods of speed reduction depending upon frictional loading and the rate at which the speed change is to take place.

In order to understand how the AC induction motor will perform with the SCR adjustable voltage controller and to determine the levels of motor current involved with the various modes of operation, the standard electrical model[1] of the induction motor will be used. Two versions of the model are shown in figure 4. The first model represents the AC wound rotor induction motor with external secondary resistance, and the second model represents the AC squirrel cage induction motor.

By varying the wound rotor model's input voltage parameter at fixed frequency, a distinct family of speed - torque curves can be derived. In addition, speed - current data can also be obtained, and when this information is mapped onto the speed - torque curve families by connecting points of equal current, very useful motor characteristic curves result.

Figure 5 shows the speed - torque - current curves of a wound rotor motor operating with 12.5% secondary impedance on an AC adjustable voltage controller. These curves show how motor torque is controlled by adjusting the average applied voltage, and the characteristic increase in motor currents for any given torque level during reduced speed operation. The curves are divided into a driving quadrant to show acceleration and running currents and maximum available torque, and a counter-torque quadrant to show the deceleration currents and torques. The full voltage speed-torque curve in the driving quadrant is extended beyond the full speed 60 Hz value to determine regeneration performance.

AC Adjustable Frequency Control

The adjustable frequency inverters of today typically use power transistors connected in a three phase bridge arrangement which is powered from a rectified and filtered DC bus. See figure 6. The controlled on-off switching action of the transistors presents a pulsed waveform to the driven motor. The pattern and polarity of the pulses is varied or modulated to produce nearly sinusoidal current in the inductive motor load. This technique is termed Pulse Width Modulation or PWM. See figure 7. By varying the width and sometimes the number of pulses in the PWM pattern, the effective average voltage and frequency supplied to the motor can be controlled.

Adjustable frequency inverters operate an AC induction motor in one of two modes. See figure 8. Again, the primary mode will be driving or motoring where the motor is doing work and delivering power to the load. When an overhauling or slow down condition is present, the mode of operation switches to motor regeneration. An induction motor operating from an adjustable frequency inverter can regenerate at any motor speed because the inverter determines the motor's synchronous speed by controlling the frequency of the applied power. The regenerated motor power is typically dissipated in dynamic braking resistors and is not returned to the power system due to the blocking action of the inverter's rectifier section.

The electrical motor models described earlier can also be utilized to determine the performance of an AC induction motor operating on an adjustable frequency inverter. See figure 4. This time, the input voltage and frequency parameters of the models are varied to derive the families of speed - torque curves. As done earlier, the speed - current data is mapped onto the speed - torque family of curves and the points of equal current are connected.

Figure 9 shows the speed - torque - current curves of the same wound rotor motor analyzed earlier but with the secondary shorted and operating on an adjustable frequency inverter. These curves show a rising torque capability with increasing inverter frequency and motor speed up to the motor's designed operating frequency, in this case, 60 Hz. Up to this point, the average applied voltage is increased as the operating frequency is increased to maintain full machine magnetization. The low speed torque fall-off characteristic can be compensated for somewhat by a low frequency voltage boost bias. At inverter frequencies above the motor's design frequency, 60 Hz, the applied motor voltage can no longer be increased. This results in a declining torque characteristic with increasing frequency due to reduced machine magnetization. This characteristic also establishes a practical upper limit of 90 Hz operation for standard motors without horsepower derating. This upper limit occurs due to converging 150% current limit operation and declining peak motor torque capability. Controlled load operation above this point can not be assured in all cases.

These curves show the driving quadrant for acceleration and running currents and the regeneration quadrant for deceleration currents. Figure 10 shows the speed - torque - current curves for a NEMA B squirrel cage induction motor which is often used with an adjustable frequency inverter. These curves are very similar to the wound rotor motor curves of figure 9, but show lower peak motor torque overhead.

Movable Bridge Loading

The induction motor speed - torque - current curves for adjustable voltage and adjustable frequency controllers that have just been shown can be used to determine the performance of these drives under typical movable bridge loading conditions. The motor loads experienced in bridge applications break down into three areas, motoring or driven loads, overhauling loads, and seating loads. Motoring loads are seen during span lifts in the case of Bascule or vertical lift bridges or during the rotate motion of rotating bridges. The constant velocity or steady state loading in these applications is minimized by counter-balancing thus leaving frictional and inertial loads to be overcome by the motor. However, ice and wind loads can add appreciably to these driven loads.

Overhauling loads are experienced in lowering a span of a Bascule or vertical lift bridge or during the slow-down of the rotating span of a rotating bridge. In lowering a Bascule or vertical lift bridge span, counter-balancing and friction act to minimize the overhauling load, and friction acts to aid the slow-down of a rotating span. Again, ice and wind loads can add appreciably to the Bascule or vertical lift bridge overhauling loads, and to the mass and rotating forces to be slowed in rotating bridges.

Seating loads occur at the end of the downward travel of a Bascule or vertical lift bridge. During the seating period, the motor will be stalled and required to produce a limited stall torque to prevent the bouncing of the span during the final lock-down phase. The load seen by the motor during this period will be a stalled, driven load.

System Performance

Precise speed control of the motor during all of these conditions is the responsibility of the adjustable speed controller. For driven loads, the AC adjustable voltage controller will gradually increase the applied voltage until the commanded minimum speed is obtained and will regulate the driving voltage during the acceleration period to follow the acceleration ramp up to full speed. The adjustable voltage speed - torque - current curve can be used to determine minimum speed running currents, acceleration currents, and full speed running currents when the load and acceleration torques are known. If the motor acceleration rate or load torques exceed the controller's preset running current limit value due to additional wind or ice loading or from an acceleration period that is too short, operation along the limiting constant current curve will occur until sufficient motor torque can be produced. Current limit acceleration will typically extend the effective ramp period somewhat due to this torque limiting action. Figure 5 shows how current limited torque will vary with speed.

Similarly, for driven loads, the adjustable frequency inverter would gradually increase the applied voltage and frequency to the motor in response to a ramped speed signal. In a like manner to the adjustable voltage system, the minimum speed running currents, acceleration currents, and full speed currents can be obtained from the adjustable frequency speed - torque - current curves when the load and acceleration torques are known. Adjustable frequency inverter current limit operation will also occur when additional acceleration, wind or ice loading is present. The effective acceleration ramp period due to limited torque will be extended. Figures 9 and 10 show current limited performance of wound rotor and NEMA B squirrel cage induction motors.

Performance of the two types of drives are similar to this point with only driven loads considered. The SCR adjustable voltage controller and the adjustable frequency inverter will handle overhauling loads in different fashions.

The AC adjustable voltage controller will accelerate an overhauling load in counter-torque and then switch to regeneration if the required speed is above the motor's 60 Hz synchronous speed value. The minimum speed, acceleration, and running currents can be determined from the counter-torque quadrant and regeneration quadrant of the speed - torque - current curves as before. See figure 5.

The adjustable frequency controller will accelerate and control an overhauling load in motor regeneration starting from minimum speed and continuing up to full speed. During this period, the motor is recovering overhauling energy from the load. Most inverters can not pass this energy back to the power system and must dissipate it in dynamic braking resistors. This requirement arises because the inverter rectifier providing DC power to the output transistor bridge will block the recovered energy from returning to the 3 phase power system. Since the developed motor torque for controlling the overhauling load depends on these resistors and the reliable operation of the dynamic braking control components, care must be exercised to provide sufficient thermal capacity in these elements.

The third type of load is the seating load where the motor must supply a controlled, limited stall torque. The AC adjustable voltage controller handles this situation easily by providing reduced current limit operation at minimum speed. This mode of operation reduces the stall torques to the required level by controlling stall currents. Figure 5 shows the level of reduced current limit operation needed for a typical 50% stall torque value.

Conversely, AC adjustable frequency inverters typically do not have a second current limit adjustment with remote selection capability. This fact and the steep slope of the inverter induction motor curves makes precise control of reduced stall torques very difficult. If a wound rotor induction motor is used, extra impedance can be added in the motor's secondary circuit that will cause the motor curve to become less steep. This method can be used to provide a controlled stall torque with a fixed minimum inverter frequency. This mode of operation, however, requires additional secondary resistors and a secondary contactor not normally needed for adjustable frequency inverter operation. These additional components require extra motor - controller interwiring and will increase submarine cable runs. This method of stall torque impedance control is not possible with NEMA B squirrel cage motors as the motor torque characteristics are not externally adjustable.

System Construction and Maintenance

The construction and control technology used in the two types of AC adjustable speed drives differ considerably. The AC adjustable voltage controller uses SCRs with a proven industrial service history of more than 30 years. These devices are typically mounted on modular, naturally convected heatsink assemblies. The system regulator's speed and current control functions are typically accomplished with simple analog methods using standard discrete components and integrated circuits. System construction is modular with replaceable system components so that field troubleshooting methods can isolate a problem to a serviceable unit. If the repair involves a printed circuit assembly, this repair can be accomplished with simple hand tools.

Most of the adjustable frequency inverters today use high voltage / high current transistors that were not available 5 or 6 years ago, and employ minimal volume packaging which requires forced convection cooling of the power handling section. This approach, while providing a small package, adds extra maintenance items in the form of limited life fans. Digital microprocessor technology, utilizing surface mount components, controls the operation of these inverters. This new technology can provide many control options, but is moving so quickly that two year old systems are already obsolete. The tight packaging and surface mount components makes field service of sub-assemblies most difficult and the repair of the PC boards with common hand tools impossible. Repair of malfunctioning units is usually accomplished by replacing the entire drive.

Emergency Operation

SCR adjustable voltage controllers can utilize existing wound rotor motors with a fixed secondary impedance. This combination allows the bridge structure to be moved in an emergency by simply bypassing the control SCRs with directional contactors. This operation is possible because the motor's fixed secondary impedance is selected to provide maximum full voltage torque at current levels less than 300% full load values. These current levels will not damage the motor or overly tax the power system.

Adjustable frequency inverters are most often used with NEMA B squirrel cage motors. Inverters can operate existing wound rotor motors as well, but, the secondary must be shorted to provide adequate low frequency stall torque. In emergency situations, full voltage by-pass techniques are not practical. The wound rotor motor with shorted secondary will produce a very low stall torque which will probably be inadequate to move the bridge structure. The full voltage stall currents of a wound rotor motor with shorted secondary will be at levels between 500% and 600% full load values. The motor control protection circuitry will trip off quickly at these levels of current to prevent motor damage. NEMA B motors provide higher full voltage stall torques but still burden the power system with stall currents at 500% to 600% of full load values. These current levels can be reduced somewhat by the use of primary resistors at the expense of adequate stall torque.

Summary

In summary, adjustable voltage drives control velocity by adjusting motor torque, and use SCRs on naturally convected heatsink assemblies. The vast installed industrial base of these systems insures a source of repair parts for decades. Adjustable frequency inverters control velocity by adjusting motor synchronous speed, and use power transistors on fan cooled integral heatsinks. This power technology is relatively new with improvements and advancements occurring each year.

Adjustable voltage drives utilize analog control techniques with standard components and IC's and are built using modular construction with serviceable sub-assemblies. Whereas, adjustable frequency inverters utilize digital microprocessor technology with surface mount components and employ unitized construction that often requires the entire replacement of a malfunctioning drive.

Driven loads are handled effectively by both systems. Adjustable voltage systems can operate an overhauling motor in counter-torque or in true power system regeneration, where the adjustable frequency inverter must rely on energy dissipation in dynamic braking resistors to handle overhauling loads. Seating loads are simple with the SCR adjustable voltage control due to the remotely selectable reduced current limit feature. Seating loads are more difficult for the adjustable frequency inverter driving a wound rotor motor with shorted secondary or a NEMA B squirrel cage motor.

And finally, emergency operation of a bridge structure is possible with the SCR adjustable voltage control with only a set of directional by-pass contactors to operate the motor across the line at full voltage. Across the line operation of wound rotor motors set up for adjustable frequency operation is impractical and across the line operation of NEMA B squirrel cage *motors* requires starting resistors which will severely limit starting torque.

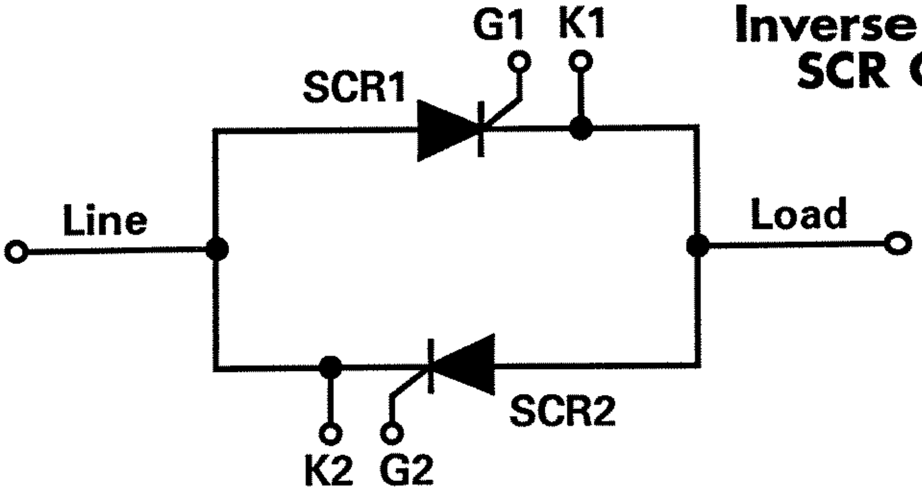
When making a choice of movable bridge control systems, the following questions should be asked:

- How are the overhauling loads to be handled?
- How will emergency operation situations be handled?
- *Can existing motors be utilized to lower the overall installed cost of the upgrade?*
- What is the expected service life of the equipment and is the system likely to become obsolete during this period?
- Who is expected to repair and maintain the equipment and can it be maintained with commonly available parts?

Answers to these questions will determine the system selection.

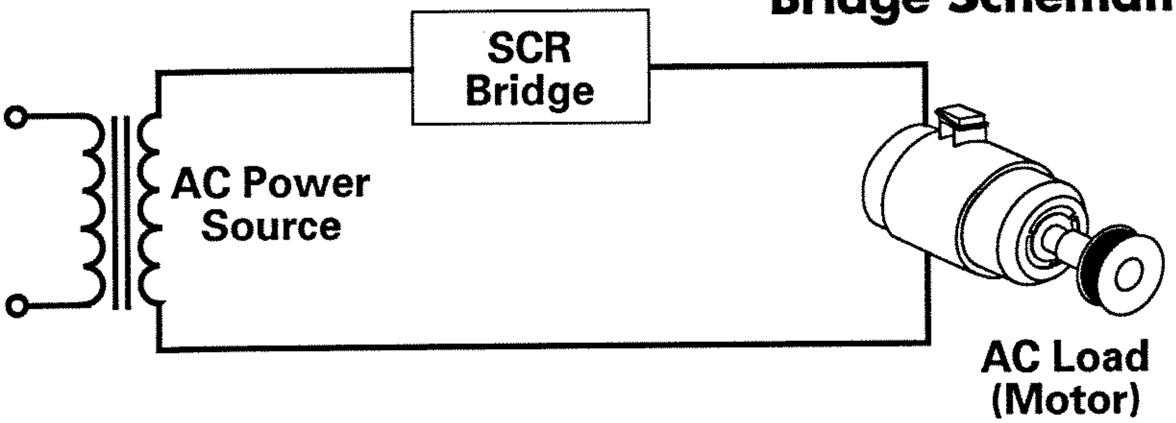
References

1. Foecke, Harold A, Introduction to Electrical Engineering Science, pg 652, Prentice - Hall Inc., New Jersey 1961



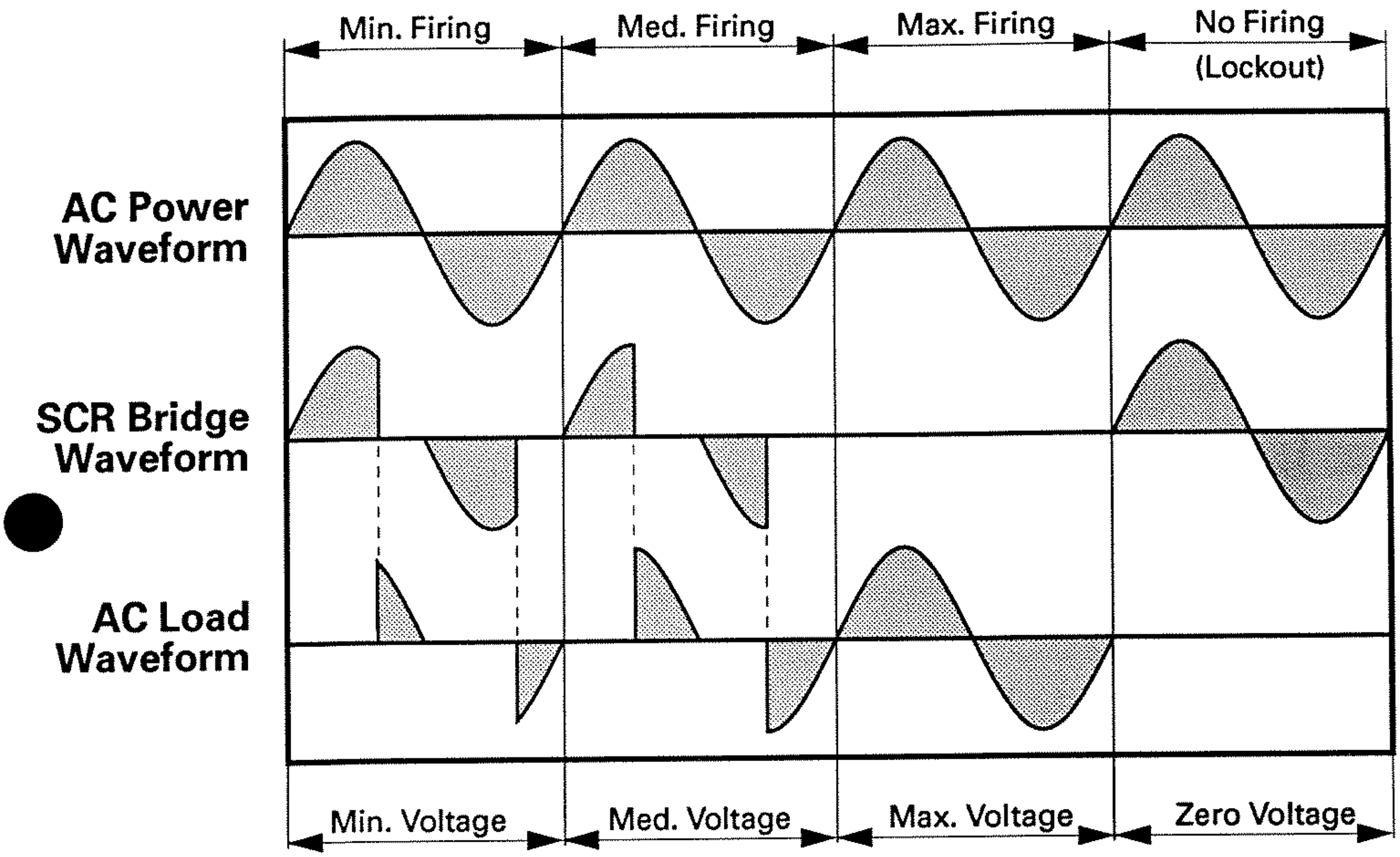
Inverse Parallel SCR Circuit

Primary SCR Bridge Schematic



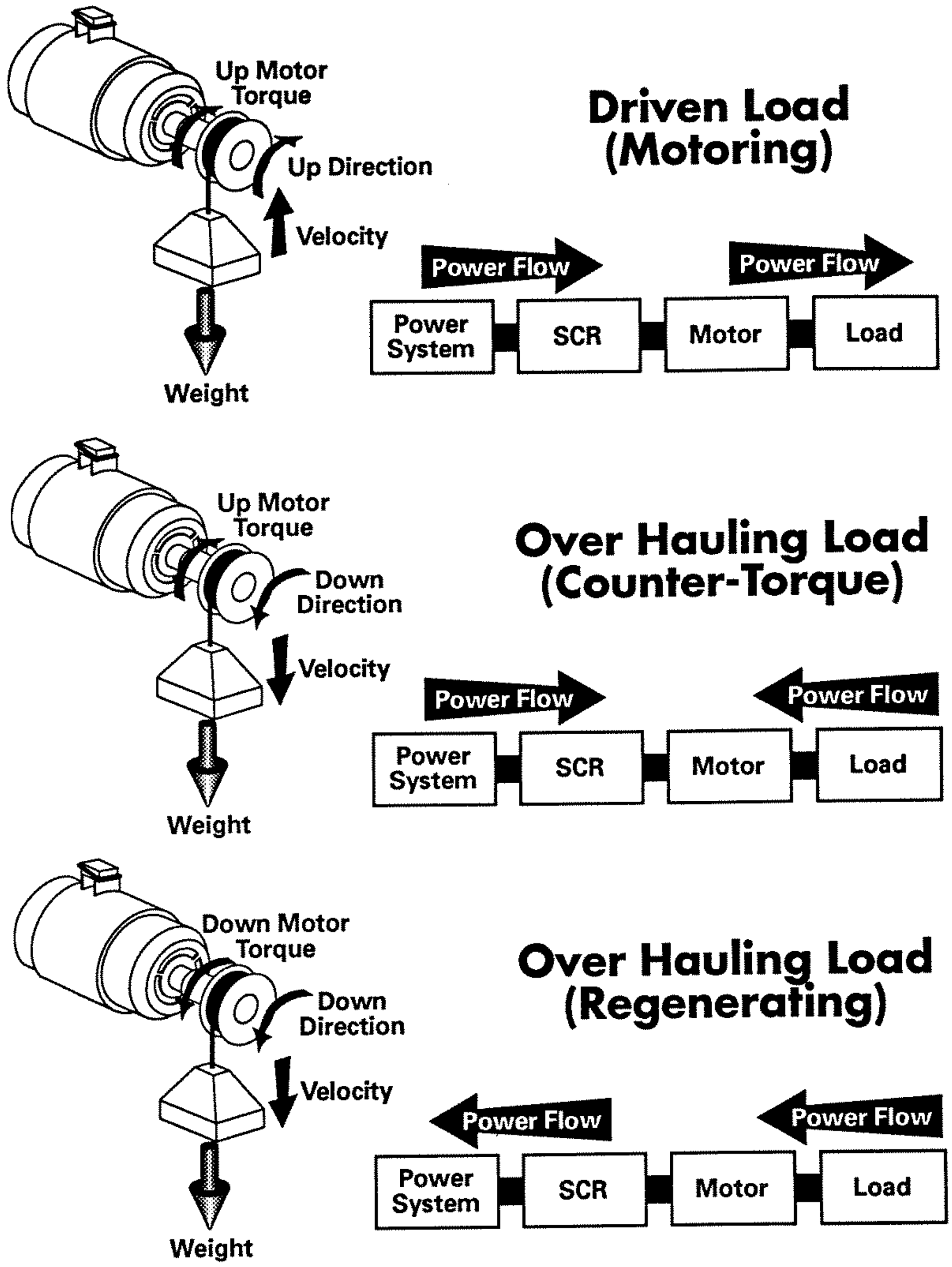
Adjustable Voltage SCR Bridge Connection

Figure 1



SCR Adjustable Voltage Control

Figure 2



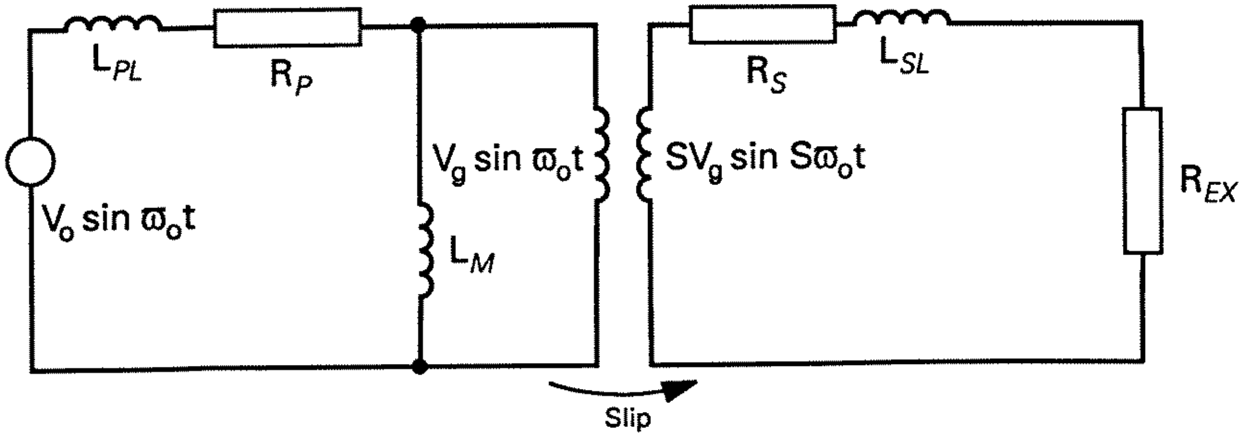
Driven Load (Motoring)

Over Hauling Load (Counter-Torque)

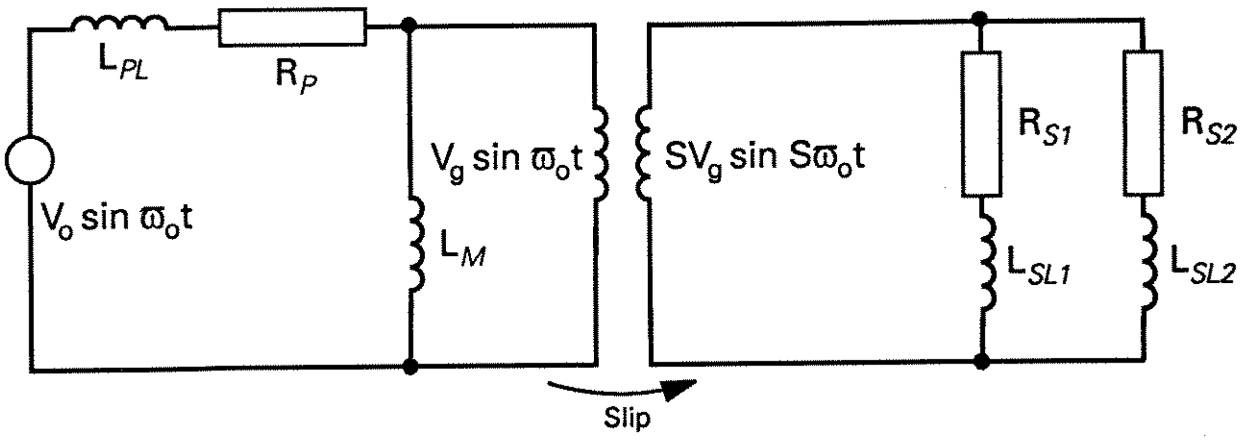
Over Hauling Load (Regenerating)

Adjustable Voltage Induction Motor Operating Modes

Figure 3

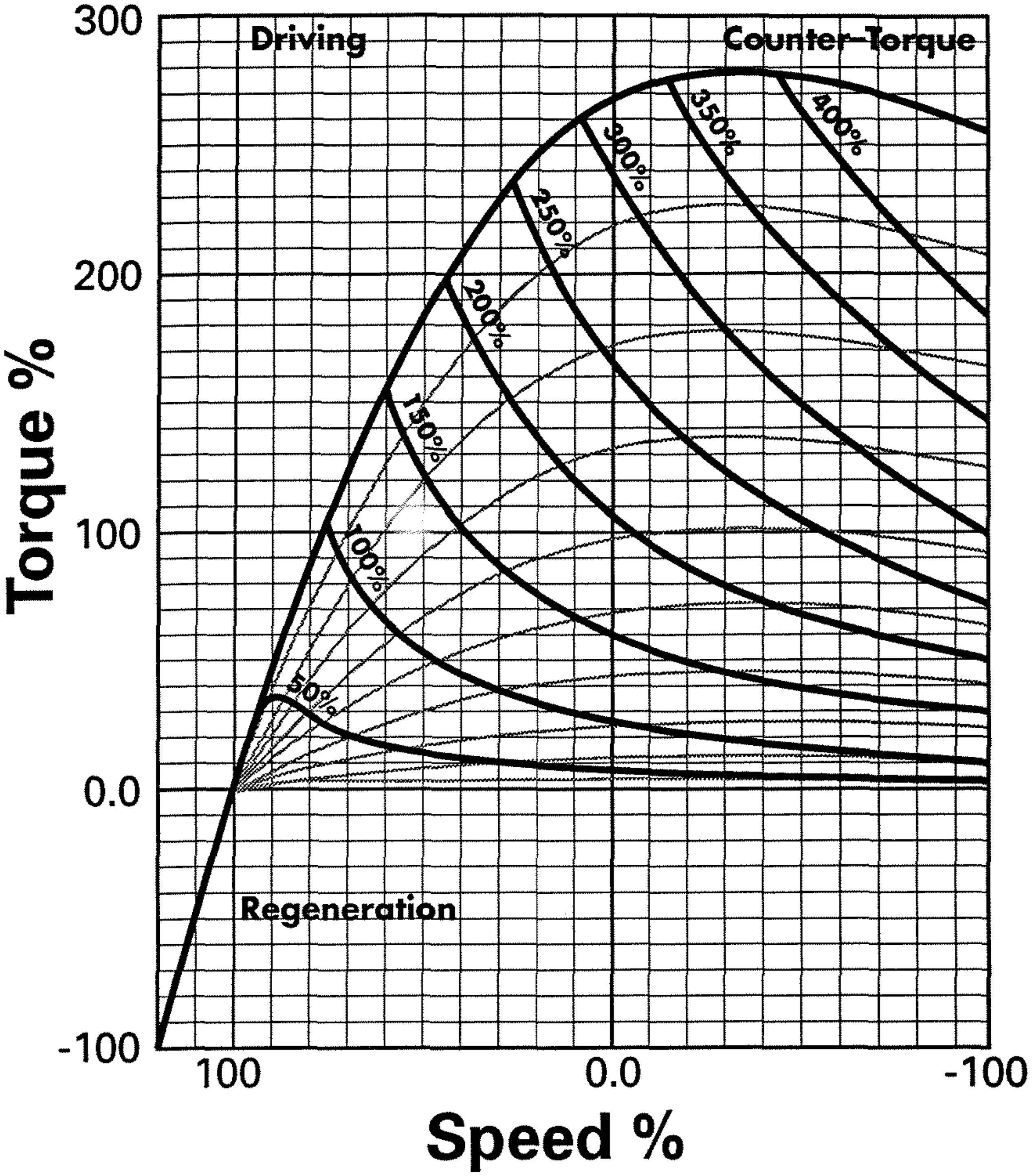


Wound Rotor Induction Motor Model



Squirrel Cage Induction Motor Model

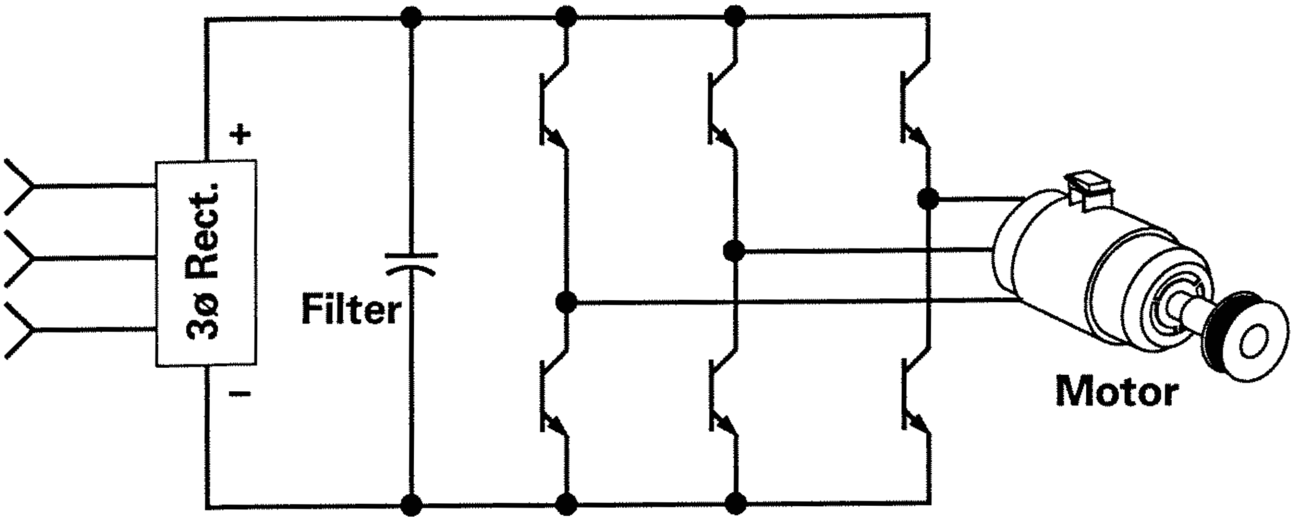
Figure 4



Speed-Torque-Current Curves for Wound Rotor Induction Motor

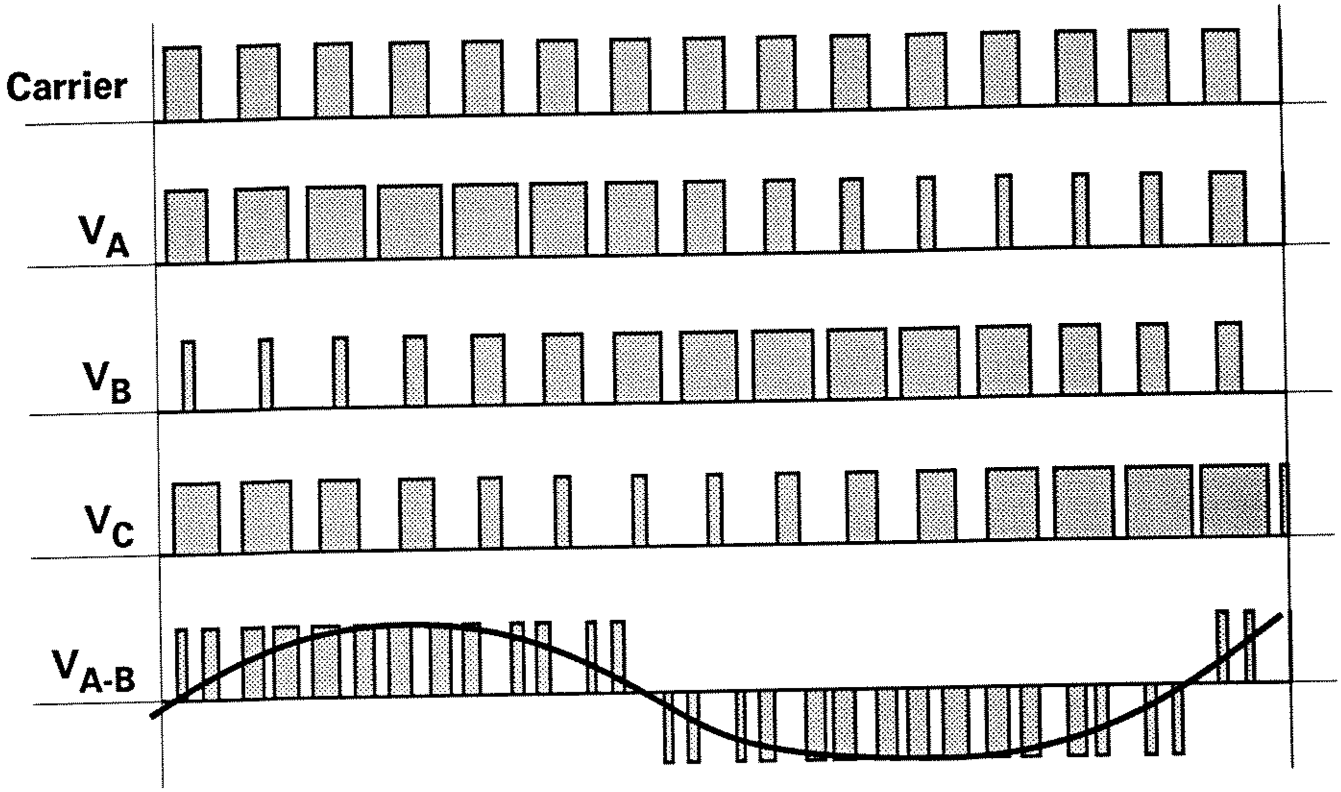
with 12.5% Secondary Resistance

Figure 5



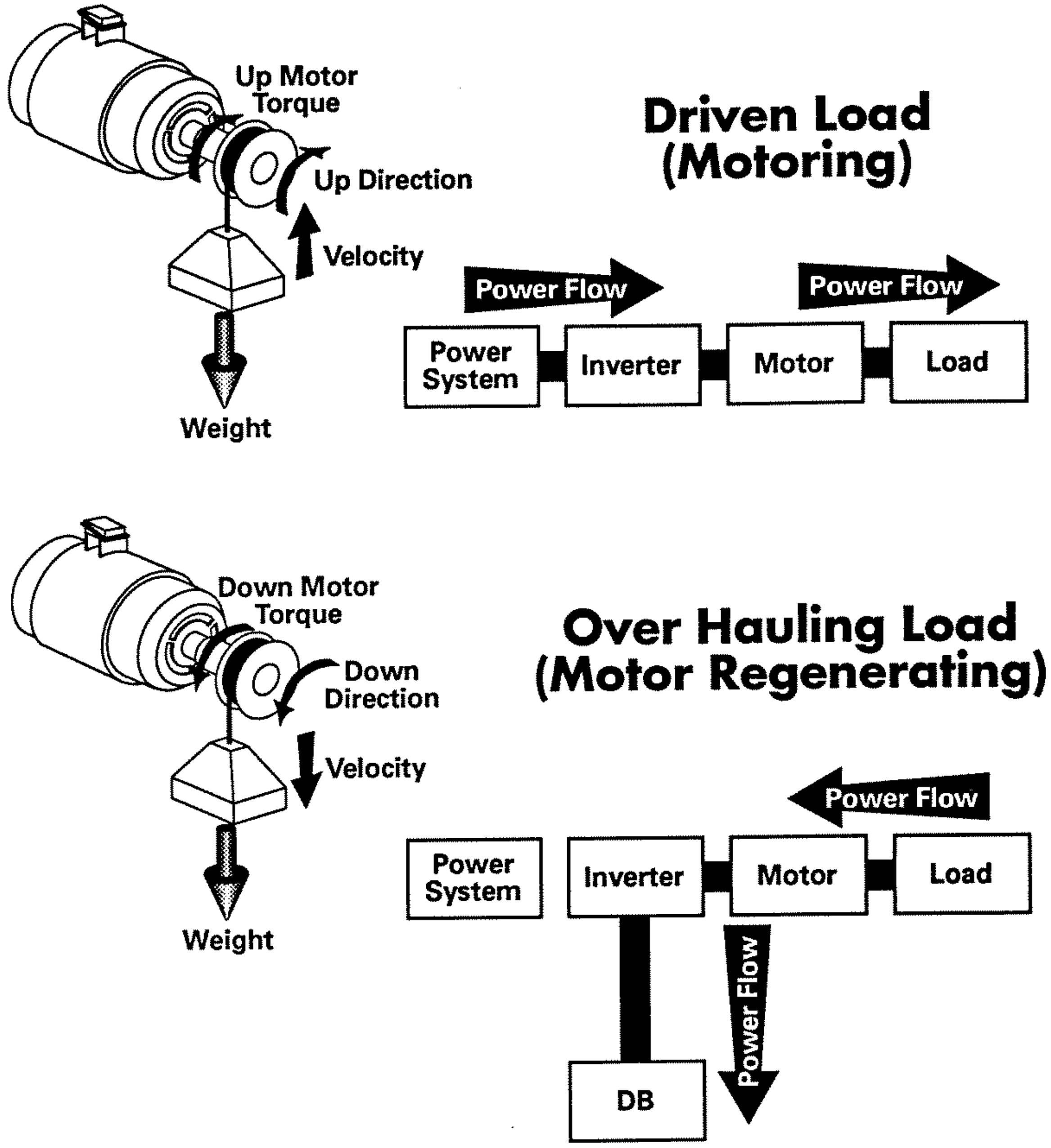
Adjustable Frequency Inverter Power Schematic

Figure 6



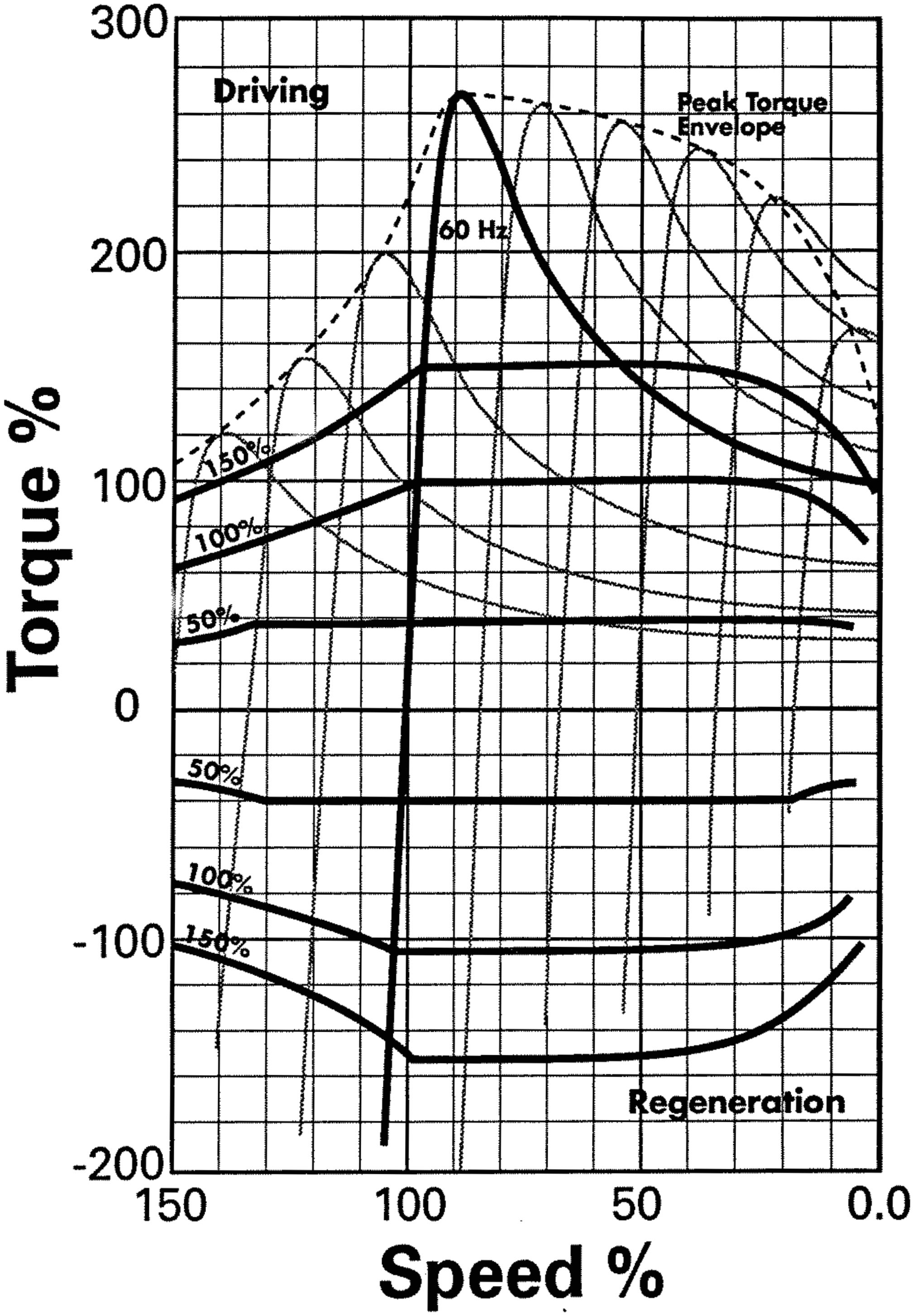
PWM Waveforms

Figure 7



Adjustable Frequency Induction Motor Operating Modes

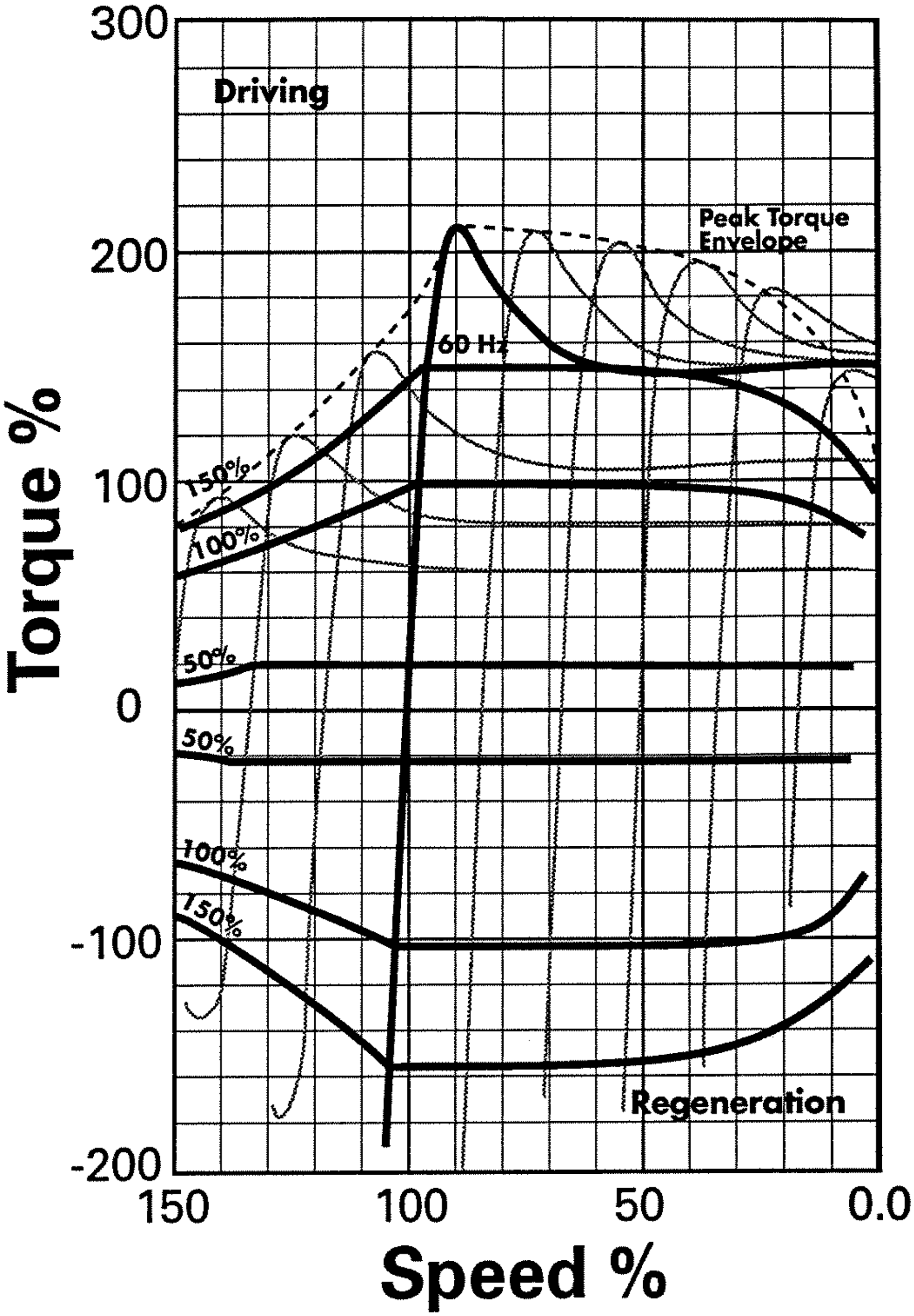
Figure 8



Adjustable Frequency Speed-Torque-Current Curves for Wound Rotor Induction Motor

with Shorted Secondary

Figure 9



Adjustable Frequency Speed-Torque-Current Curves for NEMA B Squirrel Cage Motor

Figure 10