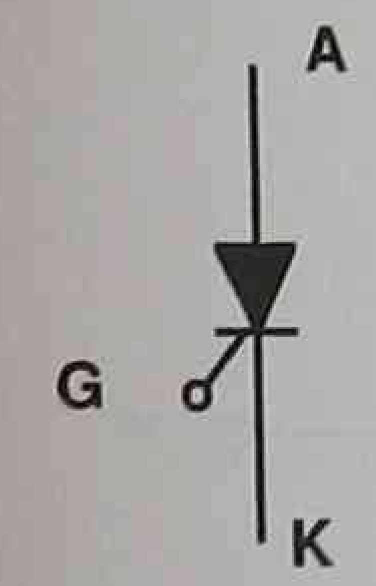
SCR LOADING OF GENERATOR SYSTEMS

This paper will discuss the effects of SCR loads on generating systems. The SCR will be discussed as a discrete device, how it is used in power switching circuits, its influences on power systems and solutions to these problems. A short discussion on other types of noise sources and their influence on generator systems is also included.

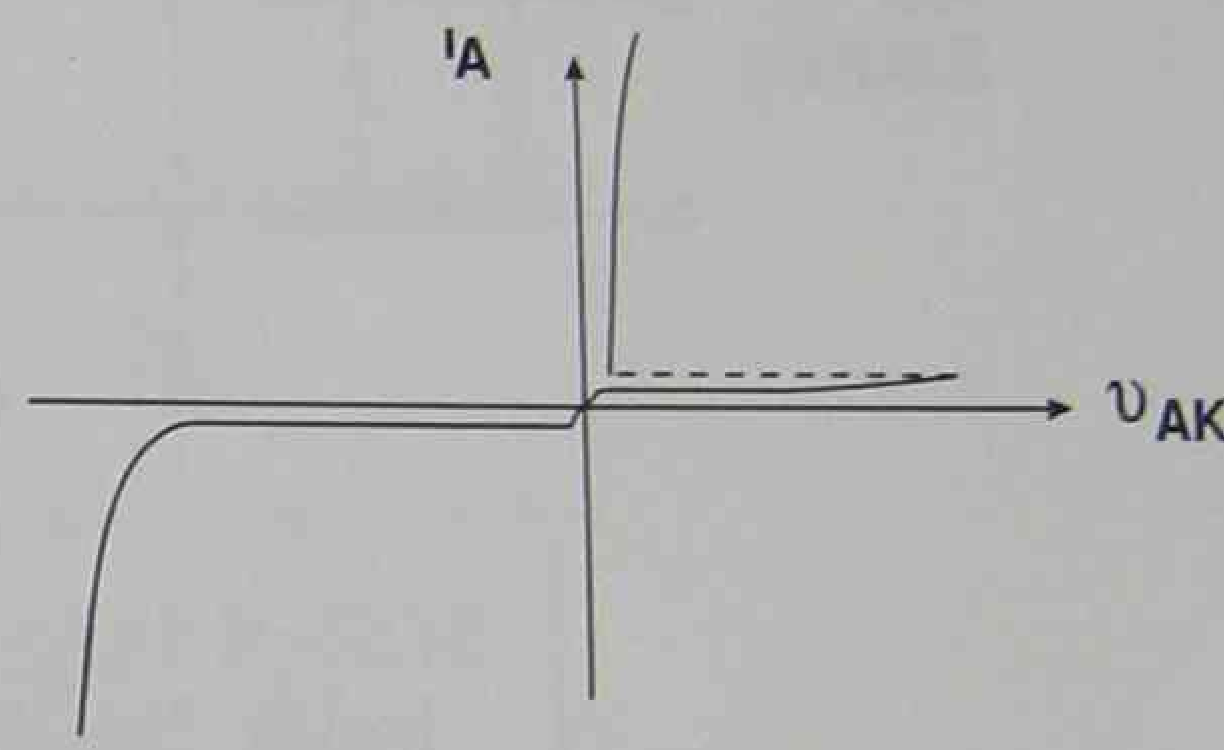
What Is An SCR?

SCR is an acronym for Silicon Controlled Rectifier. SCRs are members of the family of thyristors. The SCR is used as an electronic switch in power circuits. This switch contains three terminals, two for the main current to flow and one for the on/off control circuit (the return path for the control circuit is shared with the power circuit). The schematic of an SCR is shown in Figure 1 below.



Schematic Diagram of an SCR

Figure 1

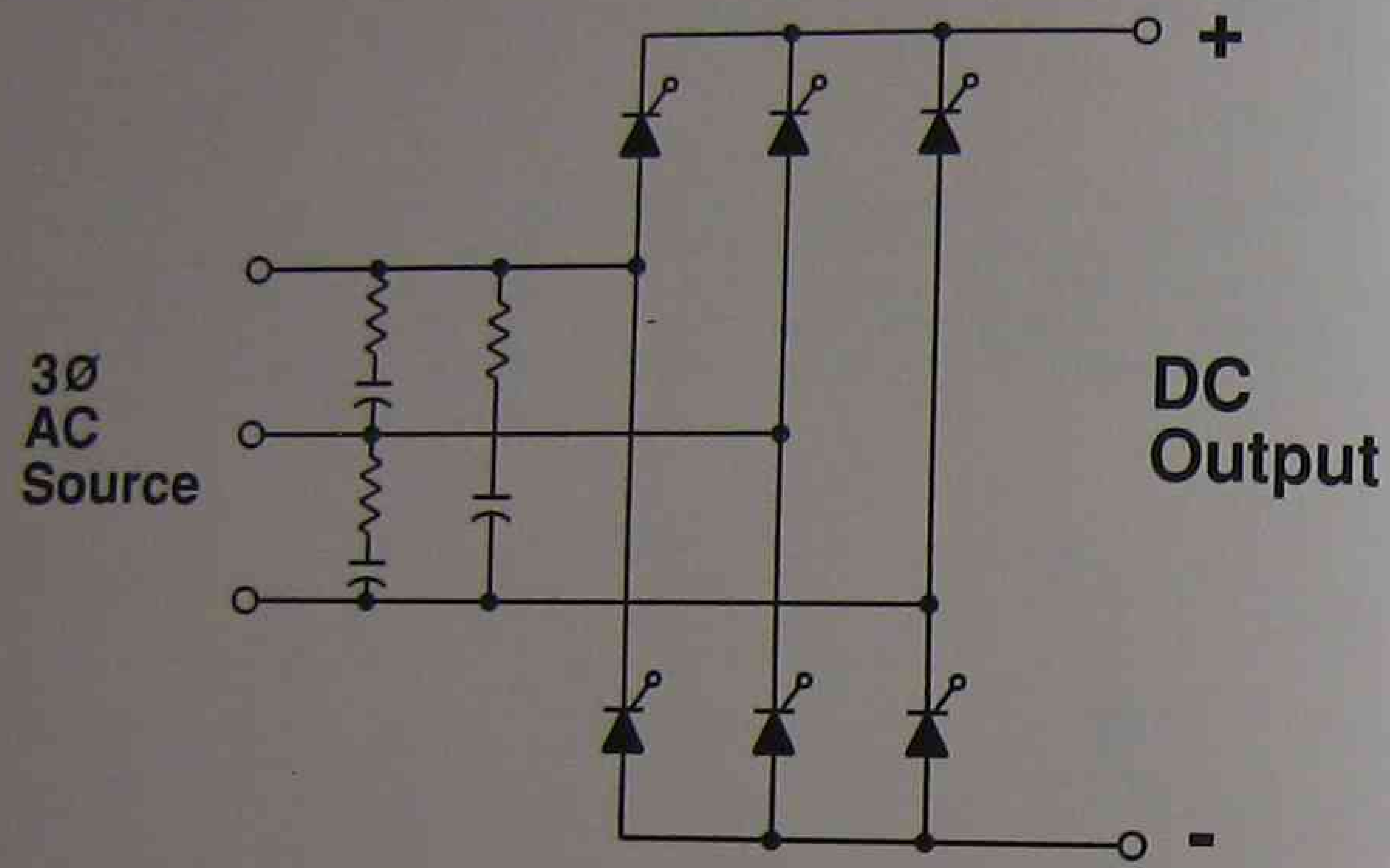


SCR Voltage-Current Relationship

Figure 2

An SCR in the "on" state conducts current like a diode, i.e. conventional current flows into the anode and out of the cathode. Reverse current is blocked just like a diode. When the SCR is in the blocking mode, current flow is blocked in both directions. The SCR is turned on by causing a current to flow into the gate connection. This is normally accomplished by applying a voltage between the gate terminal (Terminal G) and the cathode (Terminal K). If the voltage is positive between the anode (Terminal A) and the cathode, main current will flow. Once the main current reaches the latching value, the SCR will continue to conduct, even if the gate current is removed. Conduction continues until the main current is reduced to a very low value, below the holding current. The Voltage-Current relationship in the main circuit of an SCR is shown in Figure 2.

In addition, to turn on via gate control, an SCR can also be turned on by fast rising voltage in the positive direction across the anode to cathode of the device. This type of triggering is called dv/dt triggering. SCR triggering by high dv/dt is normally undesirable. To avoid this phenomena, designers usually apply a series connected resistor/capacitor in parallel with the incoming line or across each device to limit the rate of rise of voltage. These circuits are called snubbers. Snubbers can be added to existing SCR circuits to reduce their susceptibility to dv/dt triggering. An example of a snubber circuit connected to an SCR bridge is shown in Figure 3 below.

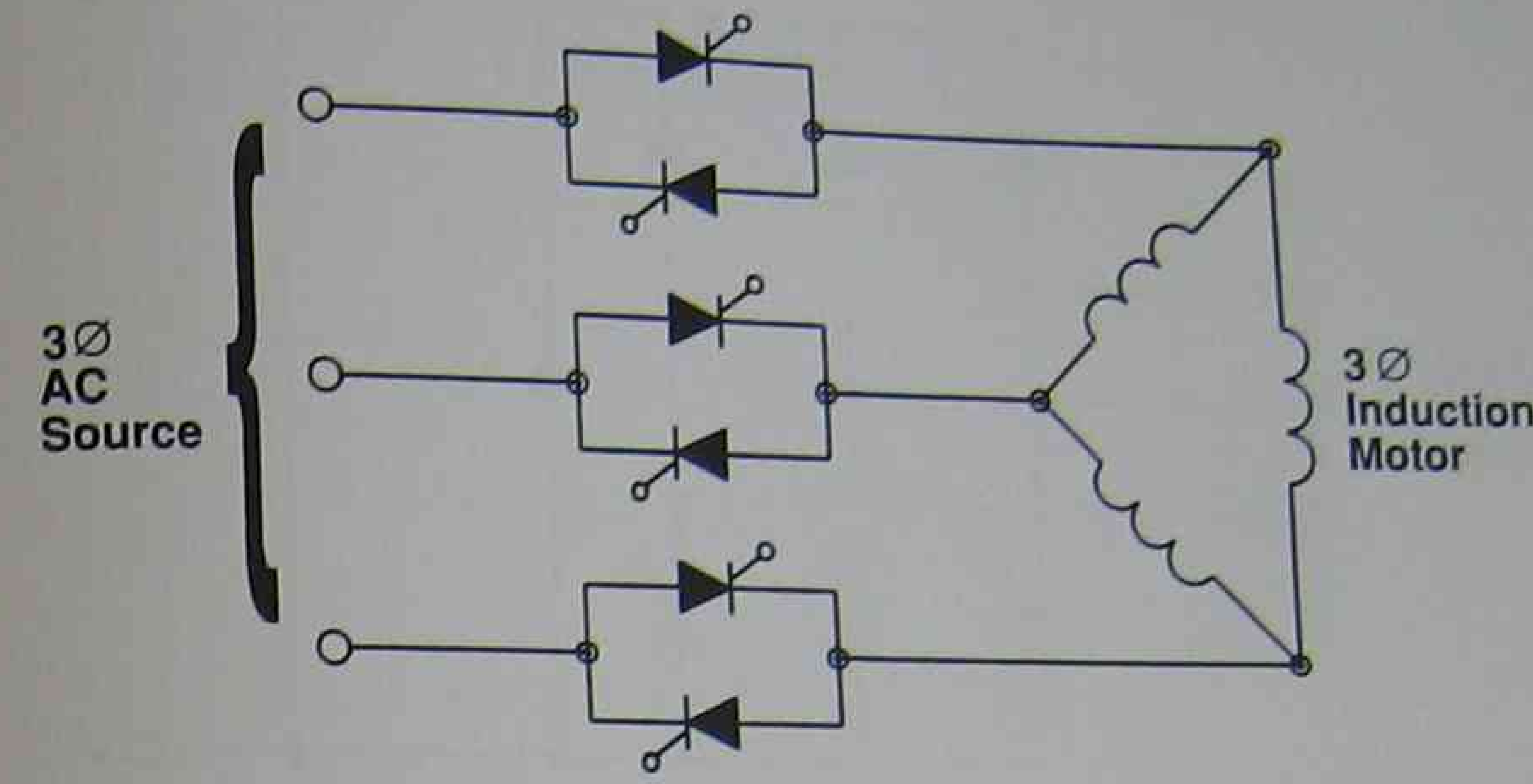


SCR Bridge with Input Snubber

Where Are SCRs Used?

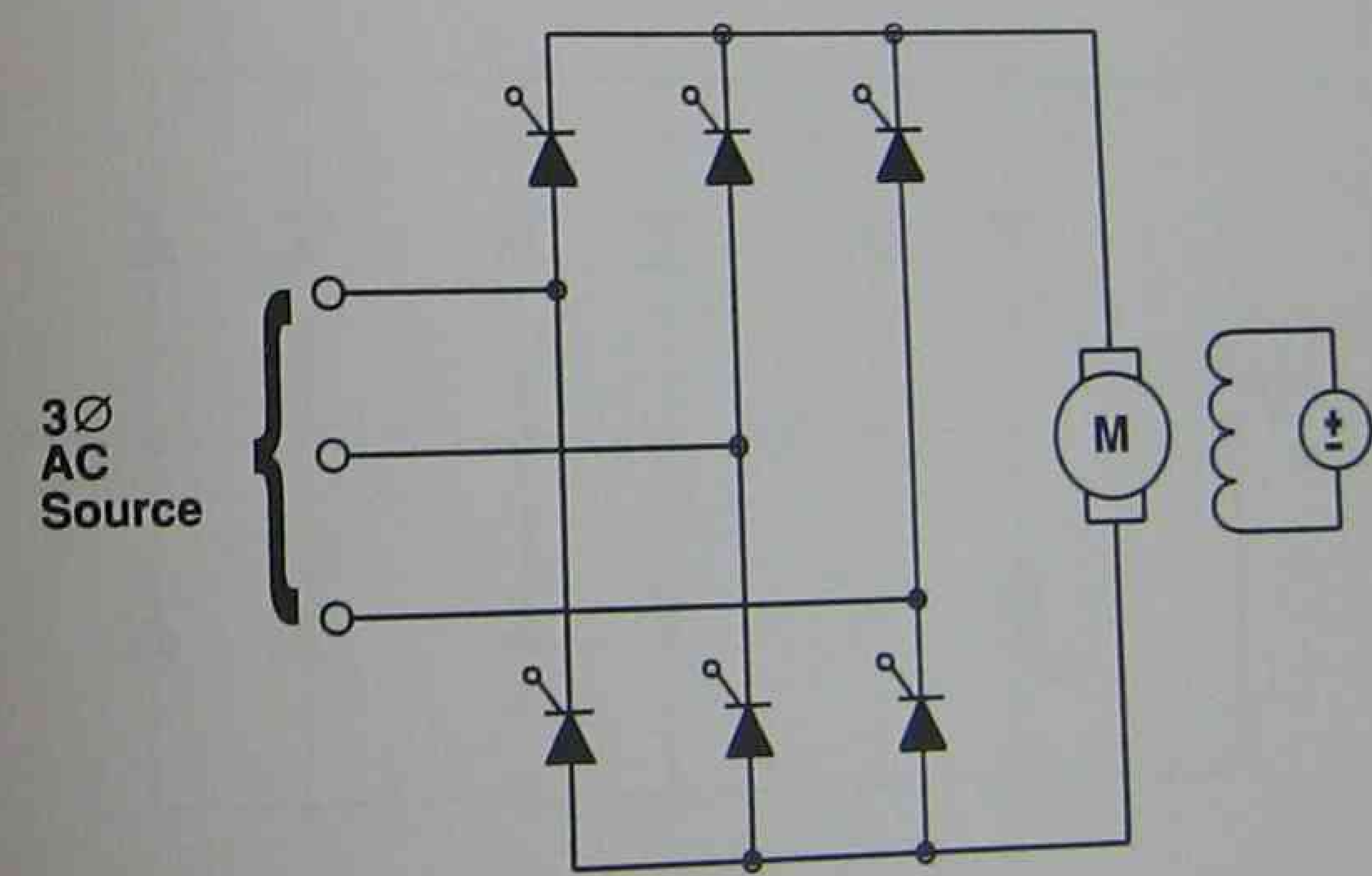
SCRs are used in many power switching circuits. They have been the switching element of choice for ac and dc motor drives, ac-dc converters/power supplies and dc-ac inverters. Designers and manufacturers of automatic voltage regulators (AVRs) and static exciters utilize SCRs in their power amplifier circuits.

Various SCR circuits are shown in Figures 4 through 9.



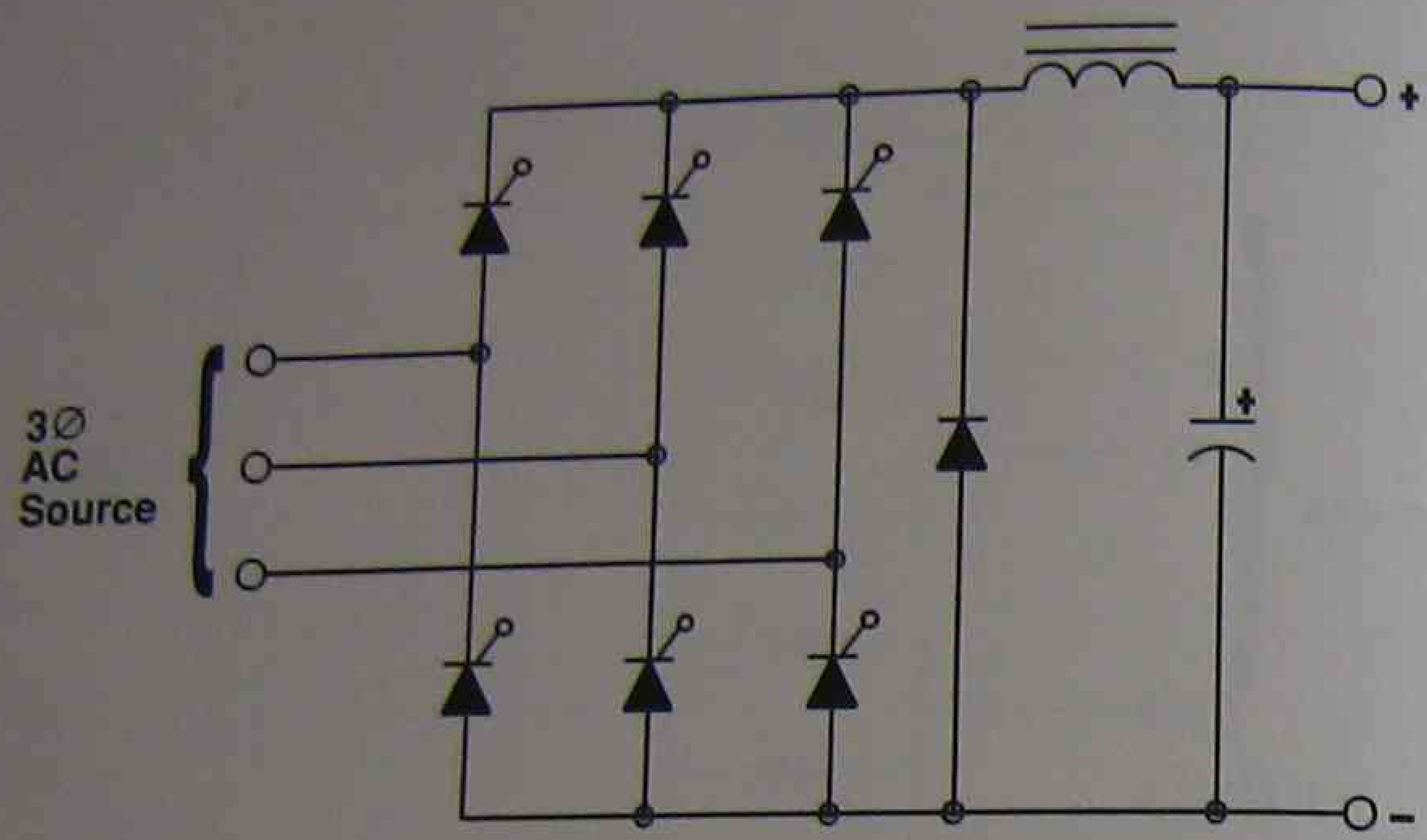
AC Motor Controller

Figure 4



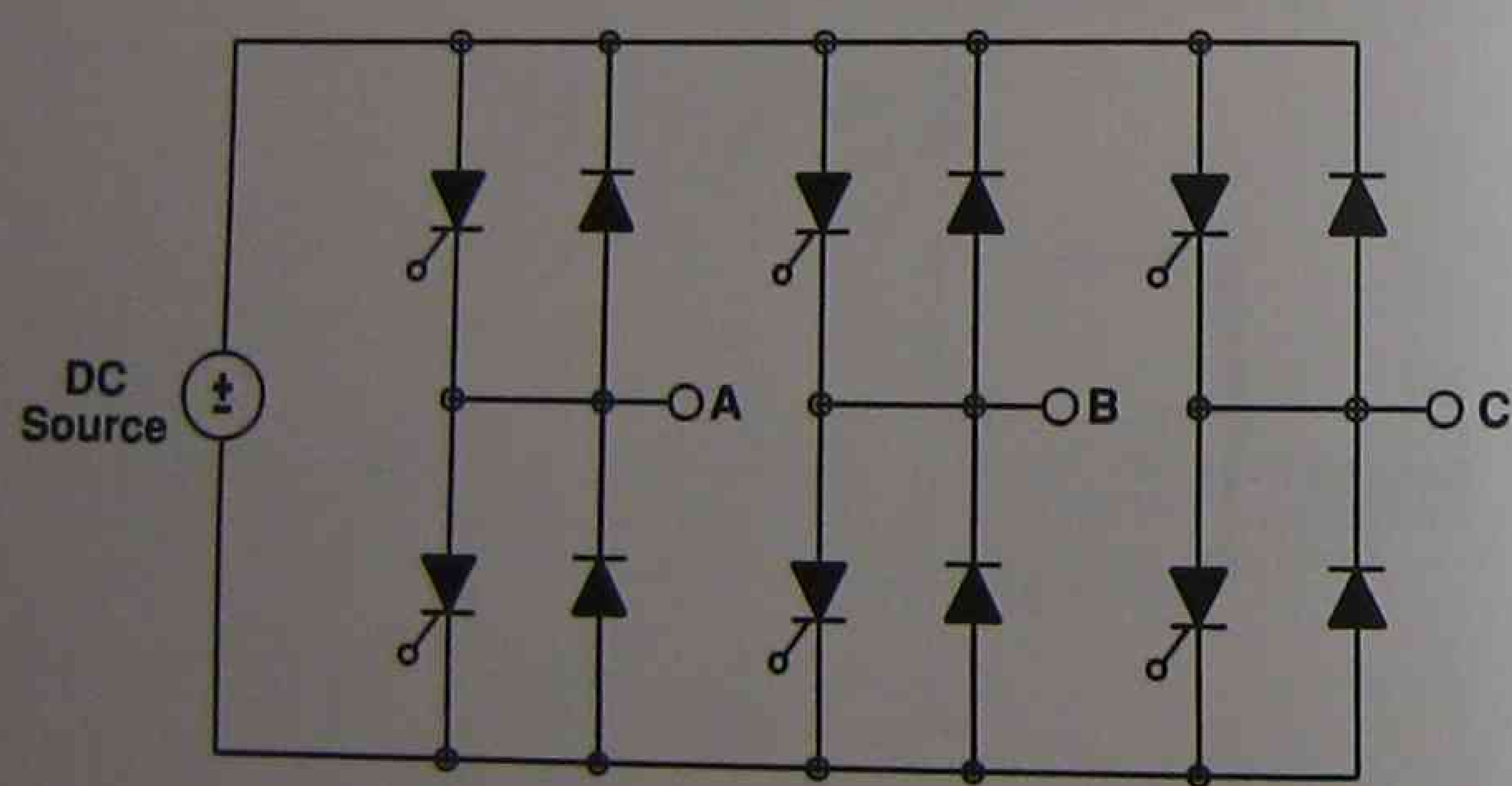
DC Motor Controller

Figure 5



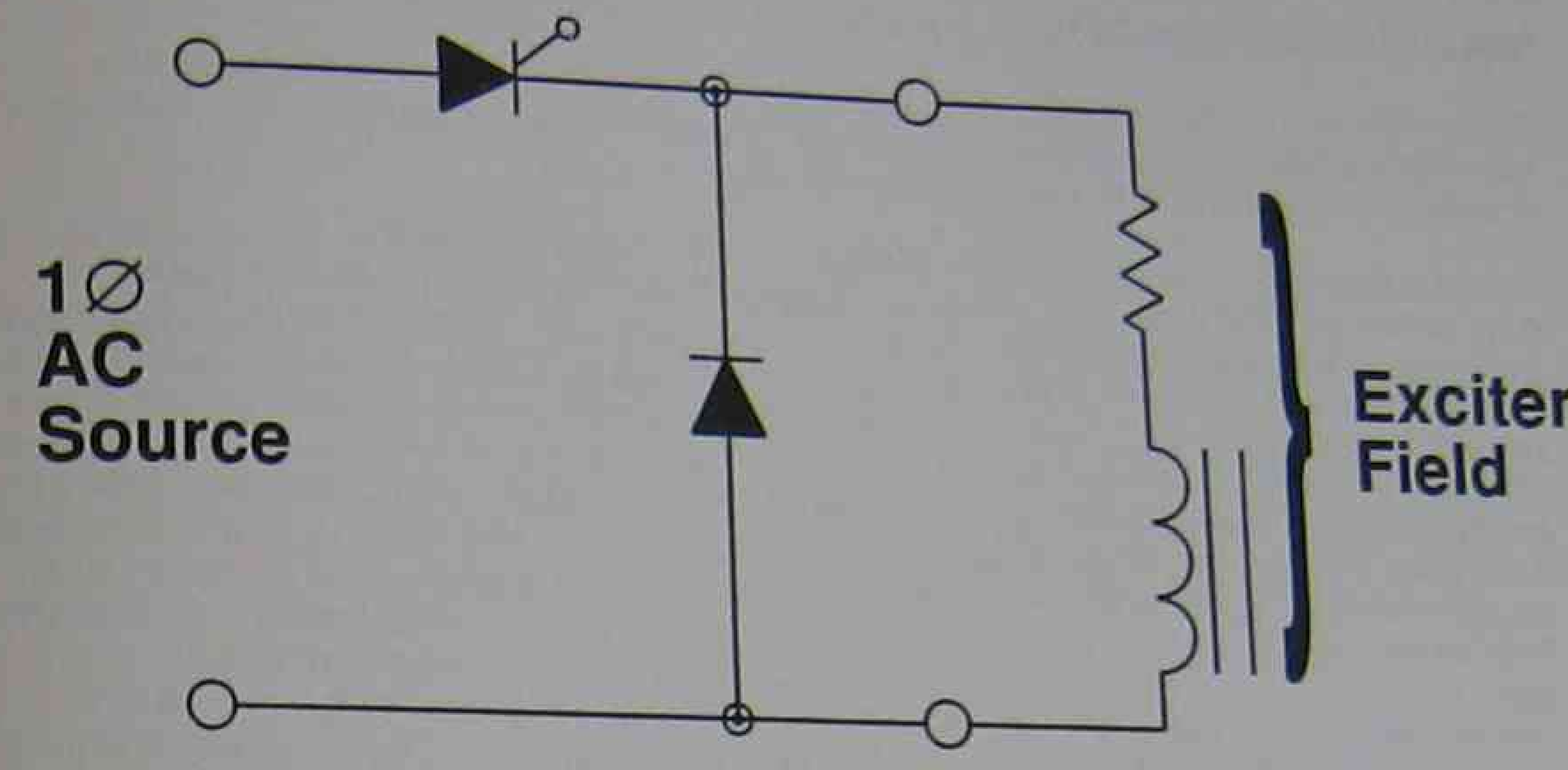
DC Power Supply

Figure 6



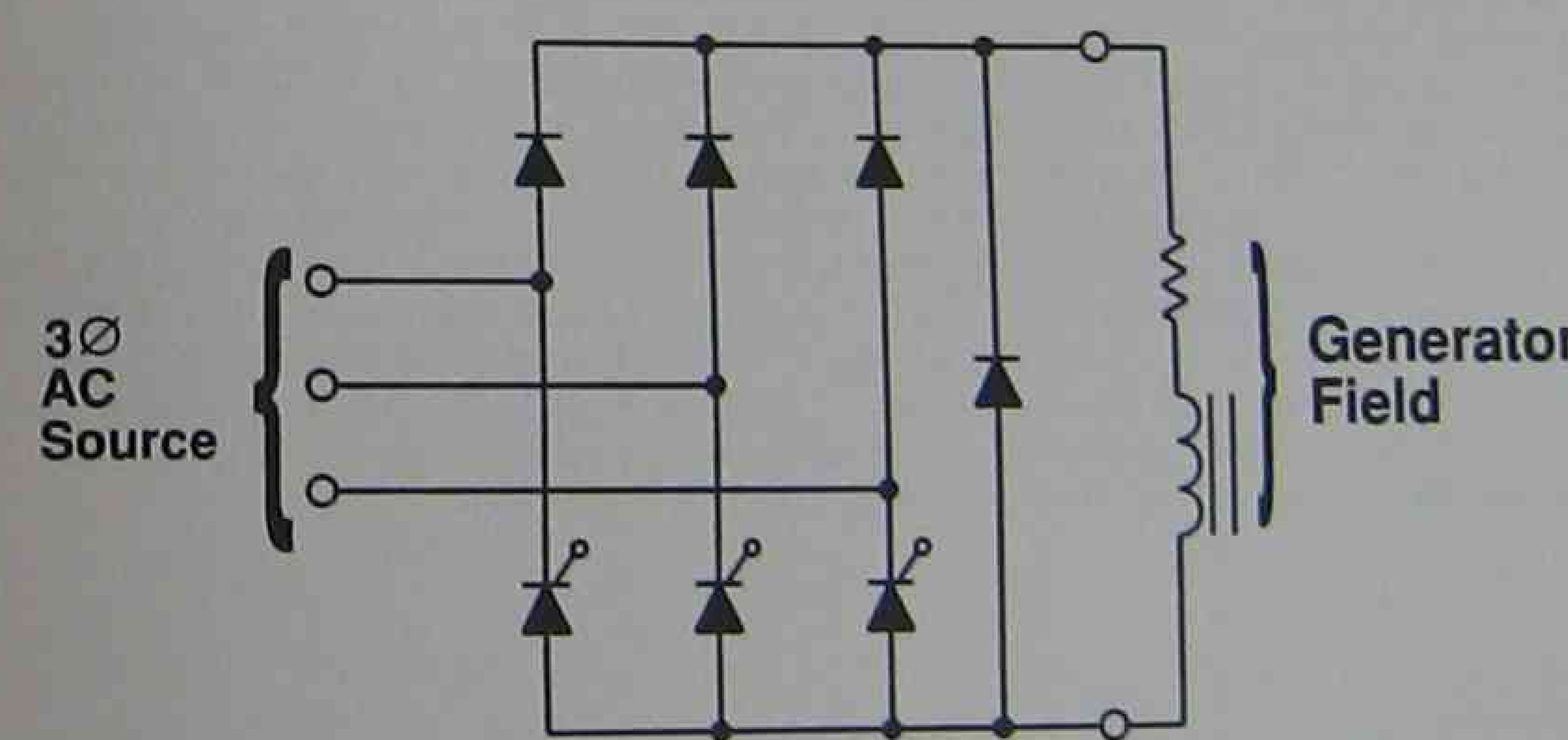
Three Phase Bridge Inverter

Figure 7



Voltage Regulator Power Amplifier

Figure 8



Static Exciter
Semiconverter Power Amplifier

Figure 9

What Characteristics Of SCRs Are Significant To Generator Systems?

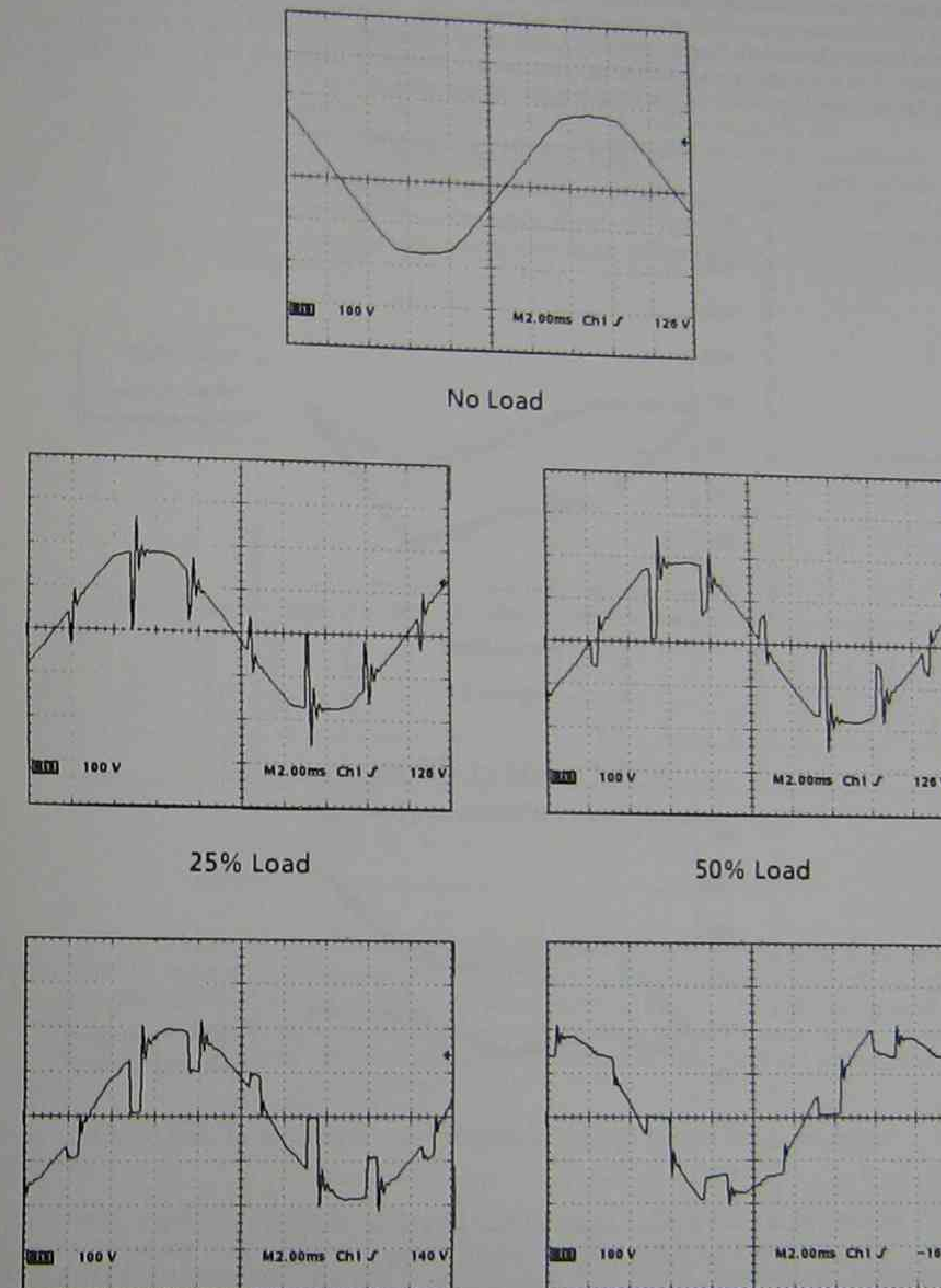
There are many characteristics of SCR circuits that should be considered when specifying/designing a generator system. These include: commutation overlap, waveform notching and high voltage spikes.

Commutation is a term used to describe the transfer of current in an SCR circuit from one branch of the circuit to another. A branch can represent a phase, line or individual SCR, depending on the circuit configuration. Commutation occurs when an SCR is gated. Current starts to flow in the gated SCR and ceases to flow in the SCR previously conducting. In practical circuits, the commutation process does not occur instantaneously. Commutation time is a function of the voltage available and the source inductance. When two branches of an SCR bridge conduct at the same time, it is called commutation overlap. During the commutation process, the two phases involved are held at essentially the same voltage. This phenomena is similar to a line-to-line short on the source. The commutation process produces a notch in the source voltage. This notch can also produce high voltage spikes once the commutation process is over. The notches and voltage spikes in the source are known as SCR noise and can cause many types of problems in generator systems. The voltage waveform of a generator source feeding an SCR load is shown in Figure 10.

How Does SCR Noise Manifest Itself In Generator Systems?

SCR noise can cause a variety of problems in generator systems. These problems include: poor voltage regulation, unstable generator voltage, influence on other thyristor loads, electromagnetic interference (EMI) and increased generator heating.

SCR noise can affect the generator waveform so severely that the RMS value of the voltage may differ significantly from the average value. This problem becomes significant when the metering system used to monitor generator voltage response is based on one method and the automatic voltage regulator response is based on the other. The RMS or Root Mean Squared value of voltage is typically used to describe the value of an ac voltage used in power systems. Some meters measure RMS directly, others measure the rectified average voltage and are scaled to read in RMS. The responses of these two systems are identical for ac voltage waveforms that are perfectly sinusoidal. As the waveform becomes distorted due to non-linear loads like SCRs, the readings that the two types of meters display can become significantly different. Many AVRs sense and respond to the rectified average value of the generator waveform. Many meters respond to the RMS value.



No Load

25% Load

50% Load

75% Load

Full Load

Figure 10

The presence of waveform distortion will cause a difference between the regulated and the monitored voltage. This can be mistaken as poor regulation of the generating system voltage when it is purely a misapplication of the AVR or metering system. Test results on a generator system with an SCR load are shown in Figures 11 and 12 for various AVR types and metering systems.

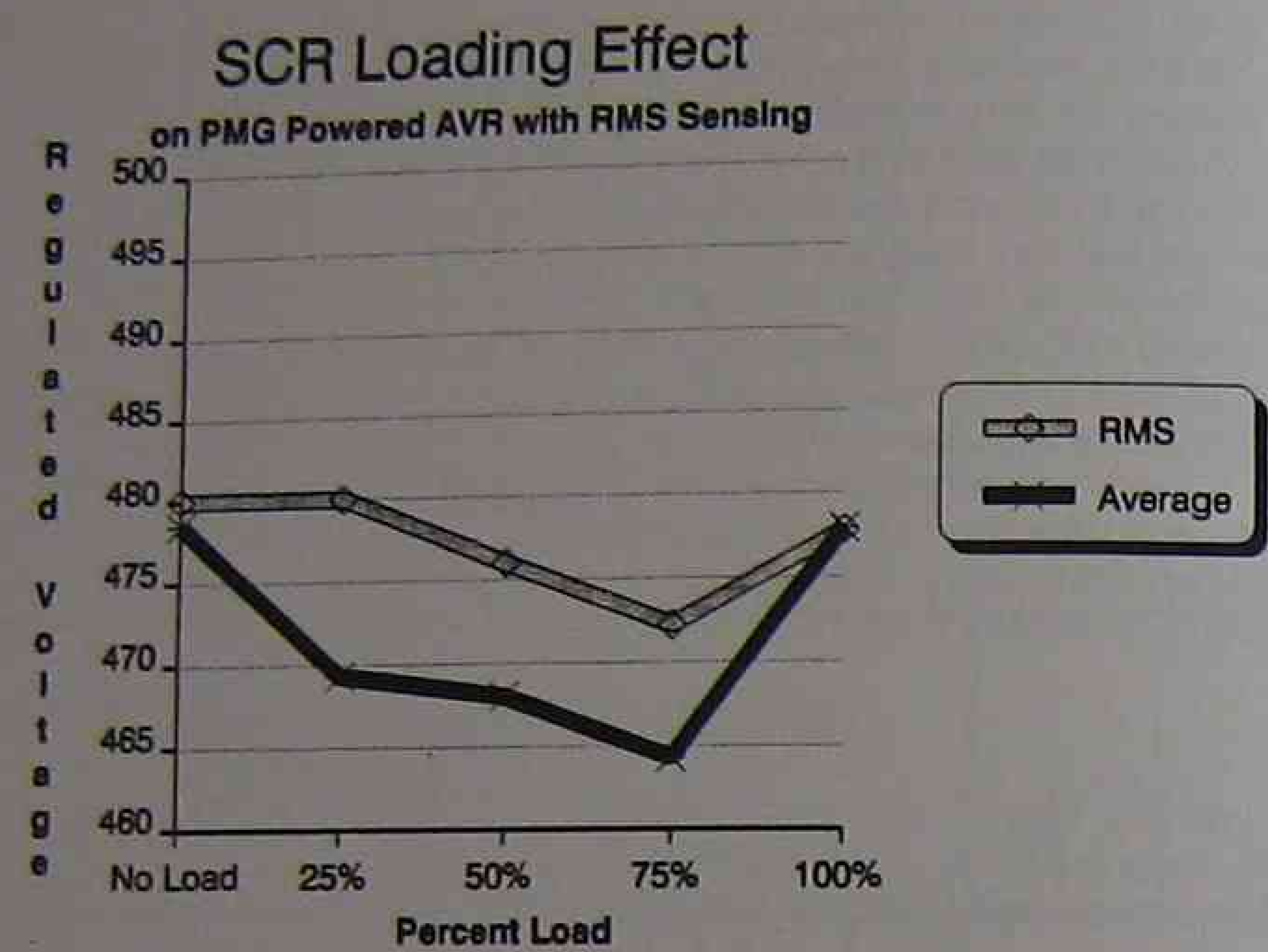


Figure 11

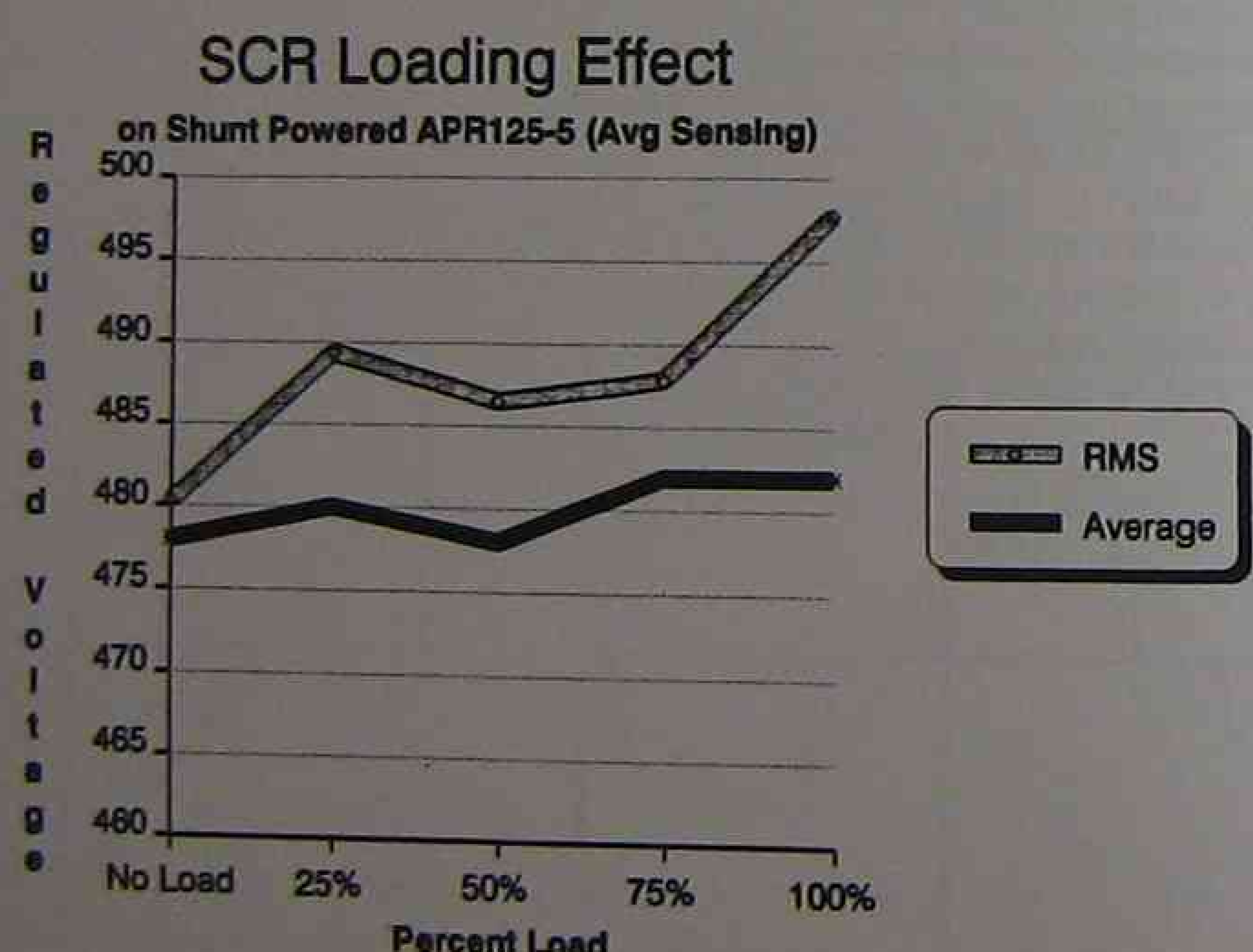


Figure 12

In addition to perceived poor regulation problems, SCR loads can cause unstable generator voltage due to the interaction between the load SCRs and the AVR's power amplifier. Many AVRs utilize SCRs in their power stage. These SCRs can be inadvertently turned on by the high frequency noise in the generator voltage on shunt excited machines. This is due to dv/dt triggering of the AVR's, SCRs and results in a loss of control of the generator output voltage. Another cause is the inadvertent turn off or false commutation of the AVR's SCRs due to a waveform notch. These notches can force the current in the AVR's SCR To go to zero, which will shut it off. If the SCR is not regated on, it will stay off until the following cycle. This also results in a loss of control of the generator's output voltage. The AVR output waveform resulting from a noise triggering and false commutation is shown in Figures 13 and 14, respectively.

Figure 13

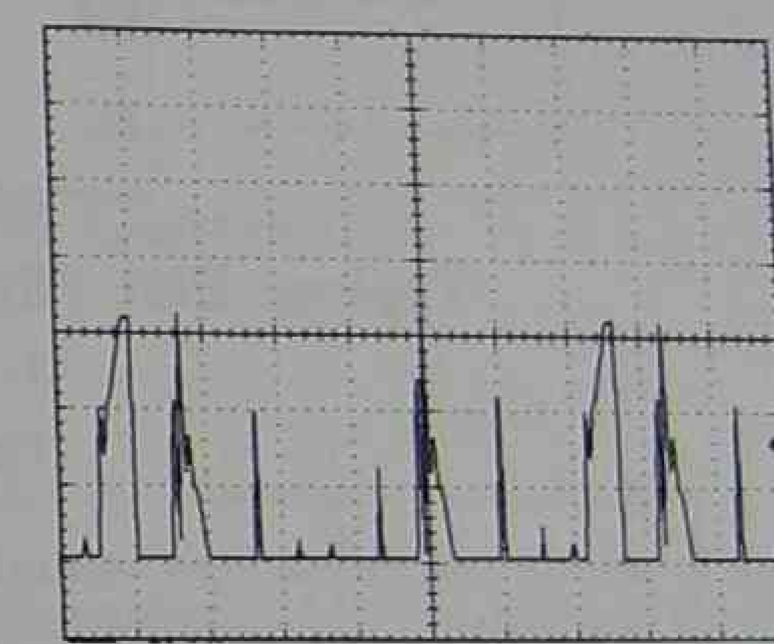


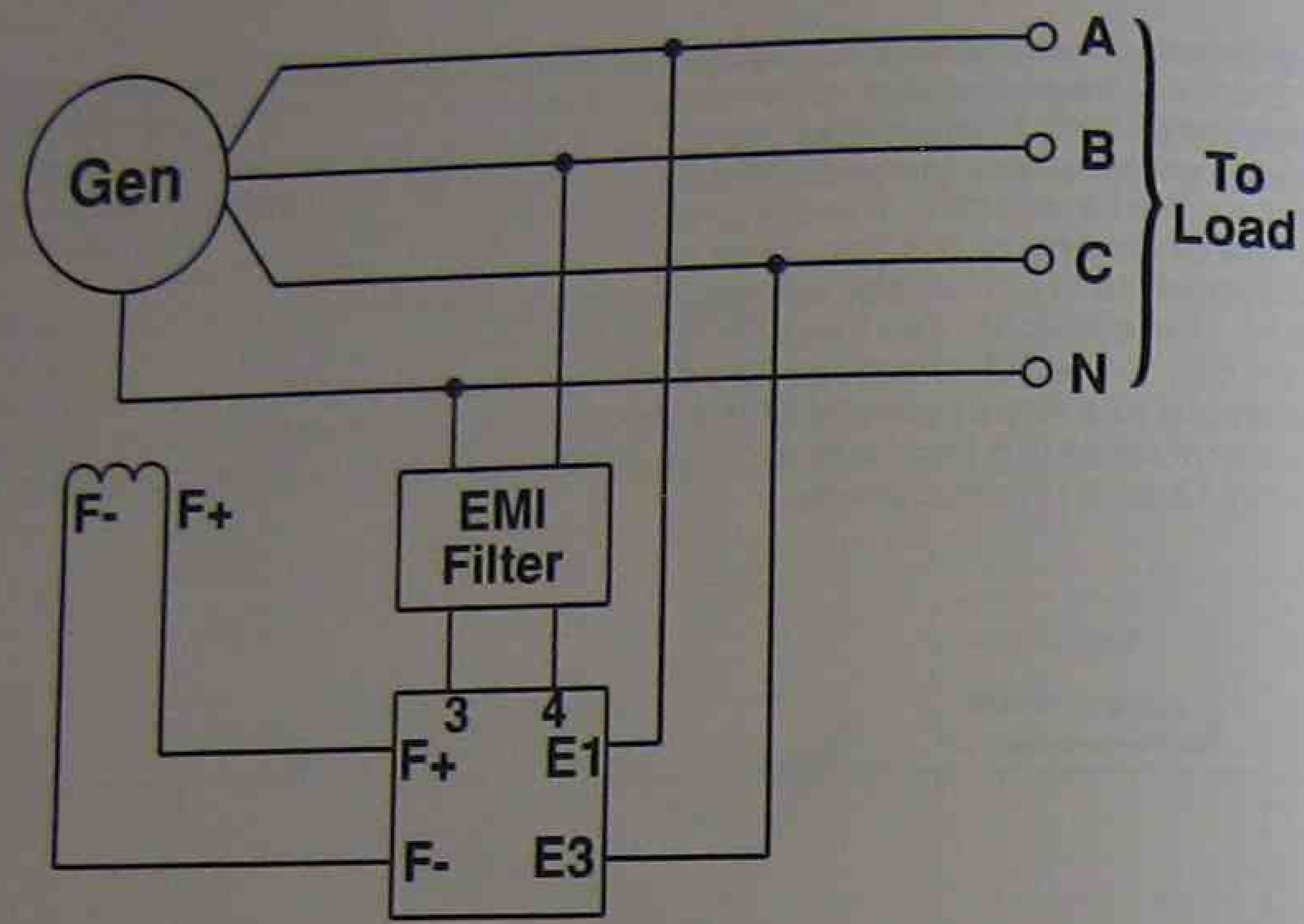
Figure 14

The presence of notches and spikes in the generator waveform can also play havoc with other loads tied to the generator. The loads may also contain SCRs or other types of thyristors that are susceptible to false commutation. The fast rising and falling edges of the voltage waveform can induce high frequency currents. These currents produce EMI that can also affect sensitive loads and increase generator heating.

What Can Be Done To Minimize The Influences Of SCR Loads On Generator Systems?

Fortunately, many solutions to SCR load problems exist for generator systems. These solutions have varying degrees of effectiveness depending on the particular problem(s) encountered. The solutions include: EMI filters, series boost options, excitation winding generators, PMG generators and AVRs designed specifically for use with SCR loads.

To keep the AVR from being affected by the SCR noise created by the load, an EMI filter can be added to the input of the AVR's power amplifier circuit as shown in Figure 15.



Typical EMI Filter Connection

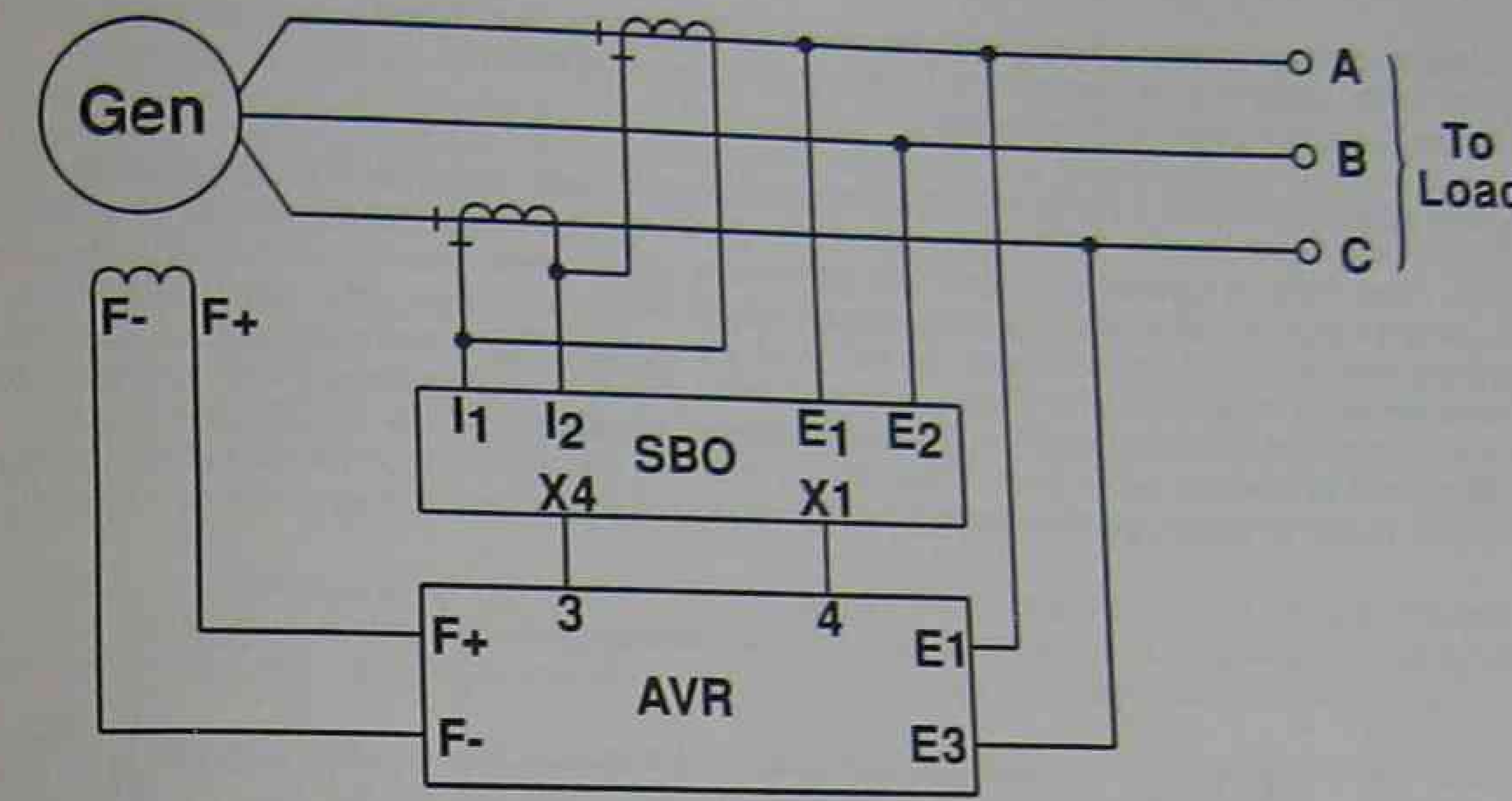
Figure 15

These filters can reduce the high frequency content of the generator voltage and decrease the likelihood of dv/dt triggering of the AVR's SCRs. These EMI filters can be sophisticated combinations of capacitors and inductors or they can be the simple snubber networks described earlier. The use of EMI filters can be effective in eliminating false triggering but will probably not be able to correct for any false commutation of the AVR's SCRs.

To assist in solving false commutation of the AVR's SCRs, a series boost option can be added. This will provide a relatively clean voltage waveform for the AVR's power amplifier stage and should eliminate any false commutation of the AVR's SCRs. A typical connection is shown in Figure 16.

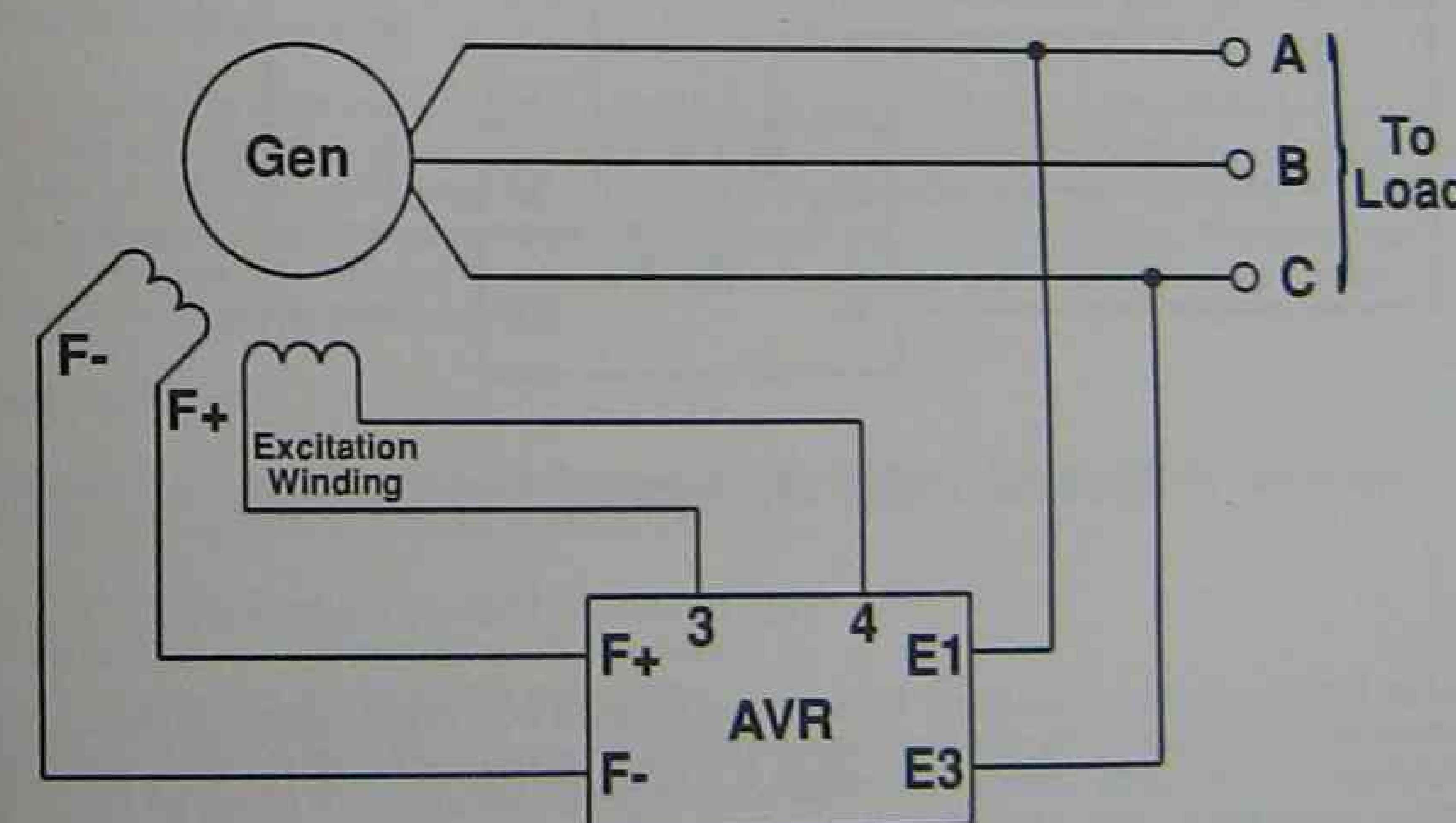
The use of an excitation winding (also called auxiliary winding) for the AVR's power amplifier input has been helpful in reducing the influence of load SCRs on the AVR's performance. A typical excitation winding connection is shown in Figure 17.

These types of generators are wound with additional windings for AVR power. These windings are electrically isolated from the main output windings and thus are not subjected to the same waveform distortion. Due to their close physical location with respect to the main windings, some high frequency noise is coupled into the excitation winding. Check with the generator manufacturer for details on the specific generator's performance in the presence of SCR loads. These windings are wound at the time of generator manufacture and cannot be added to an existing machine. Many AVRs have been successfully applied to excitation winding generators.



Typical SBO/AVR Connection

Figure 16

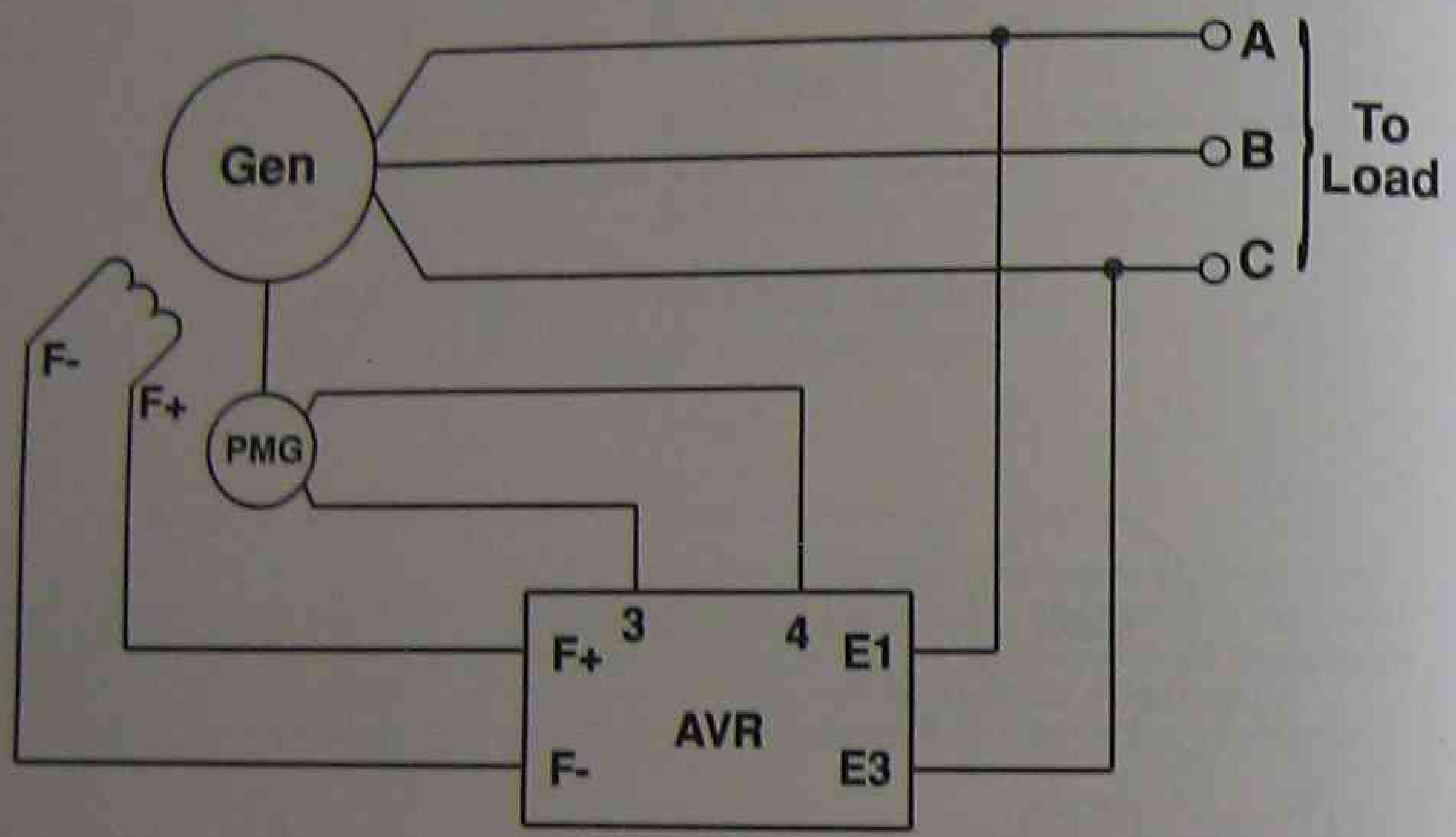


Typical Excitation Winding Generator Connection

Figure 17

The use of a permanent magnet generator (PMG) can significantly improve the generator system's performance in the presence of SCR loads. A typical PMG connection is shown in Figure 18.

These systems utilize a PMG to provide power to the power amplifier in the AVR. This totally isolates the AVR's power amplifier from the noise generated by the load SCRs. The PMG is typically part of the generator upon initial construction and should be part of the initial system specification. Some manufacturers offer optional PMG add-on kits for field installation. Check with the generator manufacturer for details. These systems require AVRs that are specifically designed for use on PMG generators so care must be taken in applying any existing AVR with an add-on PMG kit. Additional problems can occur if the AVR's sensing voltage circuit can be affected by the SCR noise present on the generator's main output.



Typical PMG Generator Connection

Figure 18

Some AVRs have been designed for specific use with SCR loads. These AVRs utilize special gating circuitry to maintain control of the generator output voltage in the presence of SCR noise. Other AVRs utilize switching transistors in place of SCRs in the power amplifier stage. This also allows for continued control of the generator voltage in the SCR noise environment.

Many solutions exist for the problems of SCR loads on generator systems. Problems can also be caused by the power amplifier stage of the AVR and its affects on the rest of the generator system. As mentioned earlier, many AVRs utilize SCRs in their power amplifier stage.

What Can Be Done To Minimize The Influences Of AVR's SCRs on Generator Output?

The SCRs utilized in the power amplifier stage of some AVRs can cause waveform distortion on the generator output voltage. Many of the previously mentioned solutions to SCR noise problems will work in both directions, i.e. from the load to the AVR and from the AVR to the load. These solutions include:

-Filtering of the AVR input with EMI filters or series boost options.
-The use of excitation winding generators.
-The use of PMG generators.
-The use of low noise AVRs with built-in EMI filters.

Other Types Of Load Noise And Its Influence On Generator Systems

There are other types of generator system loads that create electrical noise. These loads can influence generator systems in a similar manner as SCR loads. These types of loads include: ac drives, switching power supplies and communication sites.

Many new ac drives utilize power switching elements that are different than SCRs. These drives use switching transistors in a pulse width modulated inverter to provide a variable frequency ac source. The transistors switch with very fast rising and falling edges. These edges create EMI that can affect various systems within the generator system. The selective addition of EMI filters on the system can minimize the influences of the ac drive.

Switching power supplies operate by rectifying the incoming ac line then chopping it with switching transistors. This type of circuit creates EMI in a similar manner to the ac drive described earlier.

Communication sites radiate EMI by design. In some situations, this EMI can cause problems with generator systems connected directly to the transmitters or located in close proximity. These transmitters generate a powerful enough signal to create misoperation of electronic controls utilized with generator systems. The selective filtering of power and control lines along with shielding of electronics can help reduce or eliminate problems.

Conclusion

If generator systems are expected to supply SCR loads, many problems can occur. There are various solutions to these problems:

-Add EMI filters to the input of the AVR.
-Utilize a series boost option with the AVR.
-Specify an excitation winding generator.
-Specify a PMG generator.
-Utilize an AVR designed specifically for SCR loads.

DIGITAL EXCITATION TECHNOLOGY

In today's power generation systems, digital excitation technology is becoming more established as an option to the older analog excitation systems. Digital technology is being utilized in both rotary excitation and static excitation systems. It is being used on emergency standby power systems and on prime power systems ranging from small diesel generators to large hydro installations. A block diagram of a basic digital excitation system is shown in Figure 1.

Digital Excitation System Block Diagram

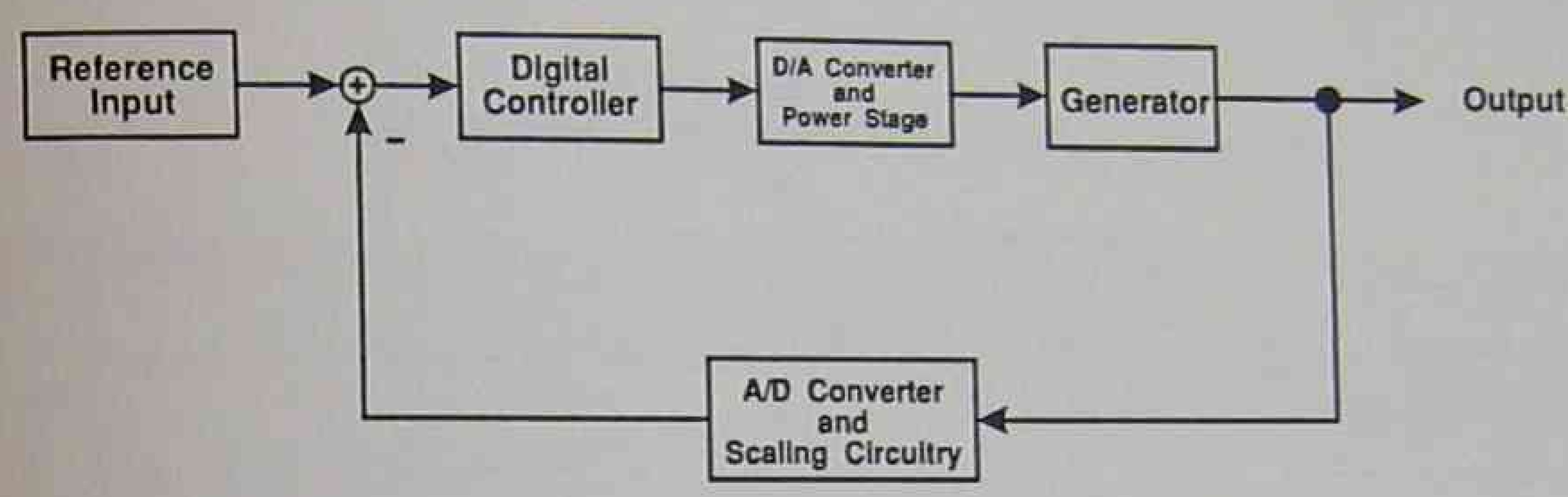


Figure 1. Digital Excitation System Block Diagram

As the block diagram shows, the digital excitation system is a closed loop feedback system. It consists of an embedded controller, an Analog to Digital converter, and a Digital to Analog converter. The plant being controlled is a generator. Both round-rotor as well as salient pole machines are being controlled with digital technology. The reference input is incorporated into the embedded controller through the use of a human interface. This interface can range from a sophisticated personal computer keyboard input to an elementary pushbutton or toggle switch input. The output of the controller must first go through a D/A converter and then through a power stage before generating the output control signal, i.e. the exciter or main field voltage. The field voltage is then applied to the generator as an input. The input of dc field voltage causes a proportional output voltage from the generator through the magnetic dynamics of the system. The generator output, terminal voltage, is then fed back into the A/D converter closing the loop on the digital excitation system.

The digital controller is essentially an embedded system which consists of a microprocessor and associated peripheral interface circuitry. The microprocessor regulates the generator's output voltage as different loads are being applied or removed from the line. This action is performed based on the sensed terminal voltage fed back from the generator output.

The controller can be used in two different modes, Manual and Auto. The Manual mode is where the controller's output of field current is regulated using an external feedback loop. The controller's output of field voltage causes a current to flow. This current is fed back into the controller's input. The Auto mode is where the generator's output terminal voltage is regulated in the presence of load variations.

This mode senses the terminal voltage and feeds it back into the controller's input. Through the use of digital control algorithms, such as P.I.D., the embedded controller regulates the generator's output terminal voltage.

The D/A converter and power stage, in the block diagram of Figure 1, is actually a combination of gate firing circuitry and a semiconductor power bridge. The digital controller's output is a pulse width modulated gate firing signal that connects to the gate of an SCR (silicon control rectifier) on the semiconductor power bridge. A typical power bridge consists of three power diodes and the power SCRs connected in a full-wave rectifier configuration. This type of power bridge requires three gate firing signals coming from the digital controller. Figure 2 shows a typical three phase power bridge hardware configuration as well as the output voltage waveforms.

Three Phase Semiconductor Power Bridge

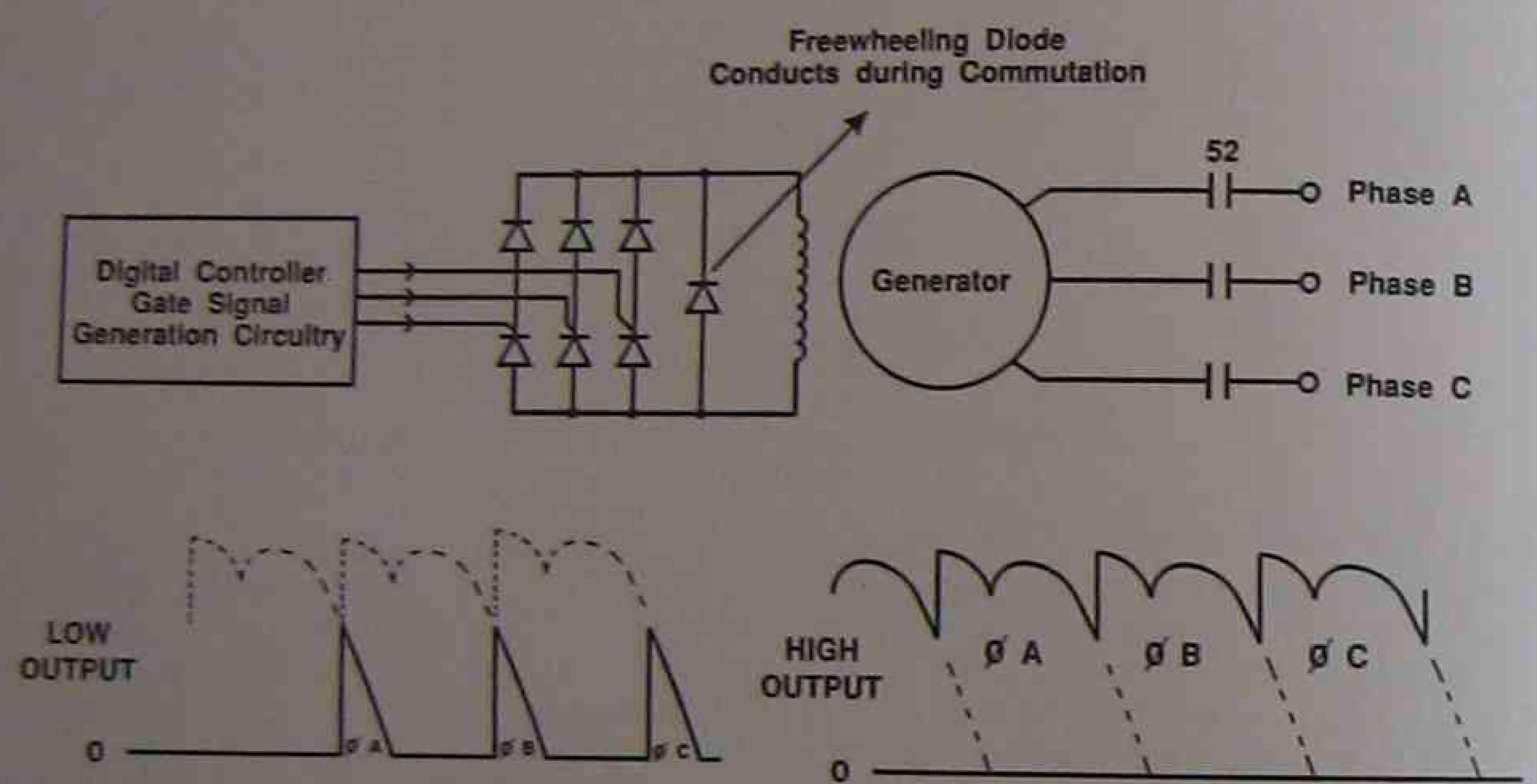
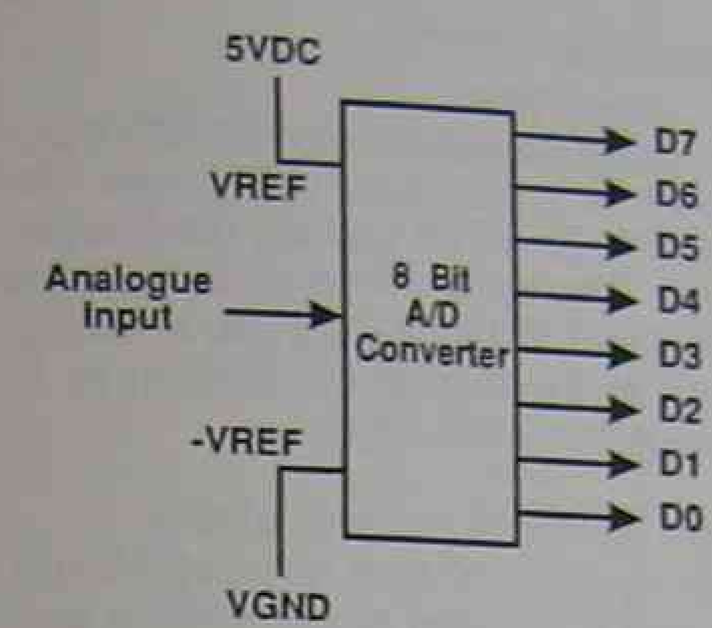


Figure 2. Three Phase Semiconductor Power Bridge

The waveforms, in Figure 2, represent both a high and a low level of output field voltage from the power bridge. The vertical rising portions of the waveform indicate the instant the SCRs are turned on. Note that as turn-on time is delayed (moved to the right), the average dc output voltage decreases. By this scheme, bridge output can be varied from full to zero output voltage. A fourth diode, called a freewheeling diode, is connected across the output terminals of the bridge to provide a safe path for field current when none of the SCRs are conducting.

The A/D converter, shown in Figure 1, is used to sense the generator's analog output voltage. It converts the analog output voltage, after scaling, into a digital binary representation that the controller can use in its regulation process. Figure 3, shown below, displays a typical eight bit A/D converter's binary output.

Unipolar A/D Converter Block Diagram



8 Bit A/D Conversion Table

Volts	Binary (D7-D0)	Hex
0.000	00000000	00
0.0195	00000001	01
0.0391	00000010	02
0.0586	00000011	03
—	—	–
—	—	–
4.961	11111101	FD
4.981	11111110	FE
5.000	11111111	FF

A/D Resolution = Max. Input/2**(Number of bits)
A/D Resolution = 5VDC/2**(8) = 5/256 = 19.53mV/bit

Figure 3. Unipolar A/D Converter Block Diagram

The A/D converter, shown in Figure 3, is configured as a unipolar device. With VREF connected to 5 Vdc and -VREF connected to digital return, the device will only convert positive analog signals. A/D converters can also be configured as bipolar devices. To configure it as a bipolar, VREF is connected to the positive voltage rail and -VREF is connected to the negative voltage rail. In this configuration, the A/D's output will be a binary representation of the signal scaled from the negative rail, through zero, to the positive rail. As the figure shows, a unipolar A/D gives a hexadecimal output ranging from 00 to FF.

The resolution of an A/D converter can be calculated by knowing what the maximum input signal is and also by knowing the maximum range of its binary output. The A/D converter, in Figure 3, has a maximum range of eight bits and a maximum input signal of 5 Vdc. Using the formula shown in Figure 3, the resolution for the eight bit A/D is 19.53mV/bit. This means that as the input changes by 19.53mv, the output of the A/D will change by one bit. So if the input changed from 4.981 Volts to 5.000 Volts, the output would change from FE to FF hexadecimal. In digital control systems, this topic of A/D resolution becomes quite important. In simple terms, the output of the digital controller can only be as accurate as its input signals. Thus a system with a higher resolution A/D converter will generate a more accurate and stable output.

Another important issue, when selecting an A/D converter, is its conversion speed. In most digital excitation systems, the signals to be measured range from 50 Hertz up to 400 Hertz. The Nyquist rule states that you must sample the incoming signals at least twice the rate of your highest frequency signal or your system will lose information. As a rule of thumb, most digital systems sample at least six to eight times the highest input frequency. This means that if your system is to be used with a 400 Hertz generator, then the sampling conversion rate of your A/D converter should be at least 2,400 Hertz.

Based on the two issues of A/D resolution and conversion speed, many digital excitation systems are using successive-approximation A/D converters. They are less expensive and they also have more resolution than flash A/D converters. Successive-approximation converters have the needed conversion rate over the less expensive dual-slope converters. The successive-approximation converters have proven to be reliable in the rugged environment where digital excitation systems are being used.

Digital Excitation Control in Voltage Regulation Systems

Digital excitation controllers are being used in many of today's power generation systems. Digital controllers are being used on generator systems ranging from 10kW up to several hundred MW. The design of the digital regulation system resembles the basic block diagram for a static excitation system. The main difference between the two is that the digital voltage controller provides the input voltage to a rotary exciter field for the exciter/generator system. Where as the digital controller, in a static excitation system, supplies voltage to the main generator field.

The basic operation of the digital voltage regulation system is to control the generator's output terminal voltage as loads are being applied and removed from the line. It does this by feeding back the sensed terminal voltage and creating an error signal based on the reference input into the controller. The microprocessor, in the digital controller, then generates an output voltage using a control algorithm. The digital controller's output voltage is then applied to the exciter field and this changes the generator's output voltage based on the magnetic dynamics of the system. A block diagram of a basic digital voltage regulation system is shown in Figure 4.

Digital Voltage Regulation Block Diagram

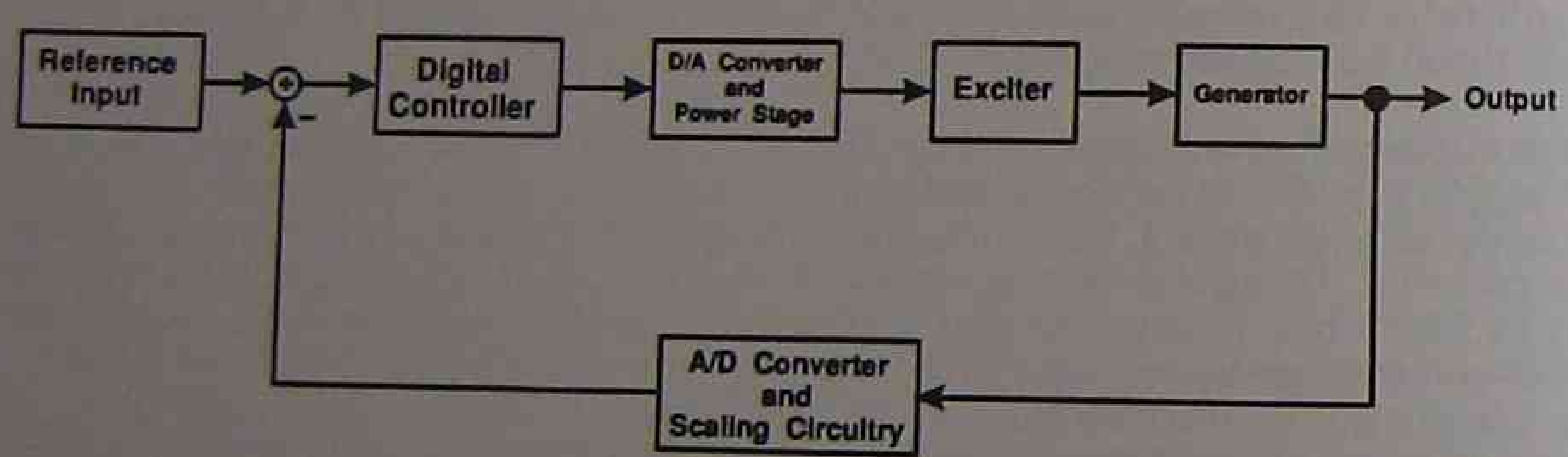


Figure 4. Digital Voltage Regulation System Block Diagram

The power stage and D/A converter section changes between the two excitation systems. In the static excitation system, Figure 1, the power stage consists of a three phase semiconductor bridge. The static excitation system used SCRs to generate the output control voltage. In the voltage regulation system, Figure 4, the power stage consists of circuitry that includes a power MOSFET transistor. The digital controller generates a pulse width modulated signal which connects to the gate of the MOSFET. By changing the pulse width of the gate signal, the output excitation voltage can be controlled as the load on the generator changes. Figure 5 shows a typical power stage for a voltage regulation system.

Digital Voltage Regulation System Power Output Stage

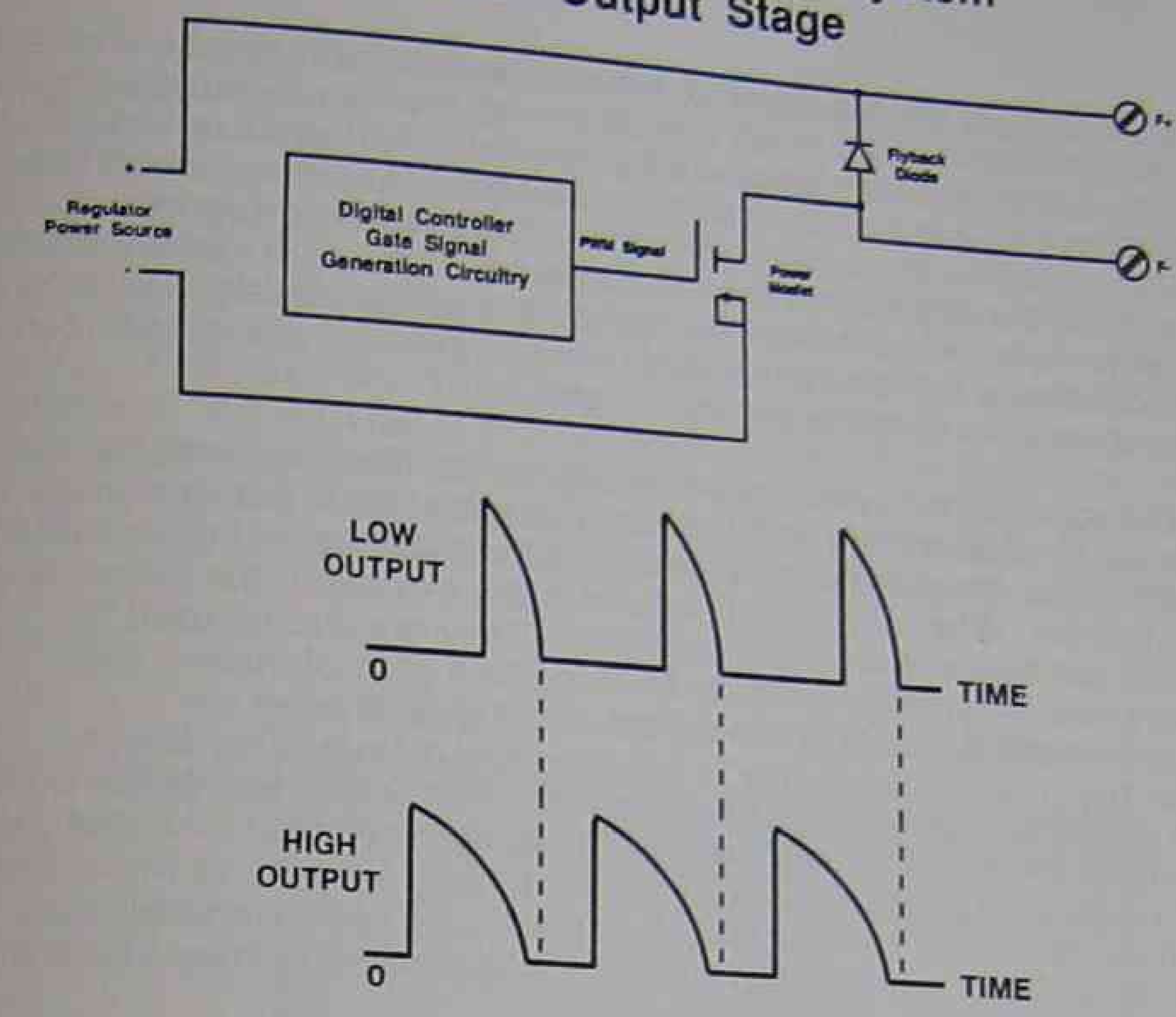


Figure 5. Digital Voltage Regulation System Power Stage

The waveforms, in Figure 5, represent both a high and a low level of output voltage from the voltage regulation power stage. The low level waveform has less turn-on time than the high level waveform. As this time changes, the output of the power stage can be varied from zero to full output voltage. The flyback diode, in Figure 5, is used to provide a safe path for field current to flow when the MOSFET is not conducting. By using this type of power stage, the voltage regulation system provides a safe and adjustable means of changing the exciter input voltage.

Analog Versus Digital Excitation Control Systems

In any discussion on excitation systems, a comparison between an Analog system and a Digital system must be reviewed. Tradeoffs have to be made in the selection of the controllers for the excitation system. Analog controllers provide continuous processing of the feedback signal and can be used for very high bandwidth systems. They also give almost infinite resolution of the signal they are measuring, thus providing precise control. Analog controllers have been around for a long time; their behavior is well understood, and this makes them easy to design. They can be implemented with relatively inexpensive components and therefore are sometimes less expensive for a minimum feature/function system.

On the negative side, analog controllers suffer from component aging and temperature drifts. Thus, a perfectly designed controller will start to exhibit undesired characteristics after a period of time. Analog controllers are hardwired solutions; this makes modifications or upgrades in the design difficult. Analog controllers are limited to simpler algorithms from classical control theory like P.I.D. and simpler compensation techniques. Analog controllers use many parts per function and therefore are more expensive for sophisticated multi-function systems.

Digital controllers sample the feedback signal at discrete time intervals. This limits the bandwidth (bandwidth is 1/6 to 1/8 sampling rate) that can be handled by the controller. The processing of the feedback signal takes a finite amount of time, adding phase delay in the excitation system. In addition, the resolution of the signal is limited by the resolution or wordlength of the microprocessor. Digital controllers also require additional components like A/D converters; although newer processors include this component on the chip itself. Digital controllers are relatively new, and their behavior is not very well understood, thus making design of digital controller relatively difficult in comparison to analog controllers.

However, digital controllers have many advantages also. They are not affected by component aging or temperature drift, and they provide stable performance. For digital controllers, the design is done in the z-domain as compared to the s-domain for analog controllers. When the design is done in the z-domain, the behavior of the digital controller can be more precisely controlled. They can also be used to implement more sophisticated techniques from modern control theory, such adaptive controllers and fuzzy logic controllers. Digital controllers are programmable, thus making them easy to upgrade and maintaining design investment. A digital excitation system can combine VAR and power factor control into the embedded controller. Analog controllers must implement VAR and power factor control as separate pieces of hardware, thus adding expense to the excitation system. Digital excitation systems have many performance enhancements that analog systems lack. A list of a few of these additional features is shown below:

Performance Enhancements of Digital Controllers

A. Line Current Limiting
B. Adjustable Stability Range and Gain
C. Local and Remote Set Point Adjustments
D. RS232 Serial Communication Capability
E. PLC Interface Capability

Most analog controllers don't provide line current limiting for their excitation systems. Digital controllers have a programmable line current limit function, which lets the user establish the limiting set point. Analog controllers use a stability adjustment potentiometer circuit that modifies the generator's output for different transient and steady state requirements. Typically the stability range for these circuits are limited and thus many not give adequate response for a wide range of generator sizes. Digital controllers use control algorithms which lets the user modify the stability for each given generator. In this way, a digital controller is more adaptable and will be able to interface to different size generators. Analog controllers don't provide a remote adjust capability. The set point, usually voltage, is changed by a potentiometer on the analog controller itself. Digital controllers, on the other hand, provide for a remote adjust capability. The operating point, of the digital system, can be changed by adjusting the controller's setpoint via raise/lower switches. Most analog controllers are not easily connected to by Programmable Logic Controllers. Digital controllers have a PLC input so that they can be interfaced into more sophisticated generator control systems. Digital controllers have RS232 communication capability so that they can interface to personal computers. By this means, they can be upgraded easily without changing the hardware configuration of the unit. Analog controllers do not have this upgrade capability, thus adding new features to an analog controller usually means redesign of the controller itself.

Waveforms of steady state voltage regulation were taken for both an analog controller and a digital controller. The waveforms, in Figure 6, show voltage

regulation over a span of 15 seconds. The voltage setpoint was 480 Volts on a 300kW generator. The analog controller has better steady state regulation than the digital controller. The reason for the difference in regulation is that the analog controller is a continuous time system and the digital controller is a discrete time system. The analog controller will act on any size change in its sensing input. The digital controller, on the other hand, reacts to discrete levels on its sensing input due to the resolution of its A/D converter. This translates to a wider change in its steady state stability. As the waveforms show, the analog system has steady state regulation of 0.25 percent. The digital system has a steady state regulation number of 0.5 percent. The difference in steady state regulation is due to the inherent A/D resolution of the digital controller. If the resolution of the A/D converter was increased, the steady state stability would improve. With all the features a digital system has, a digital controller is the right choice for today's excitation systems.

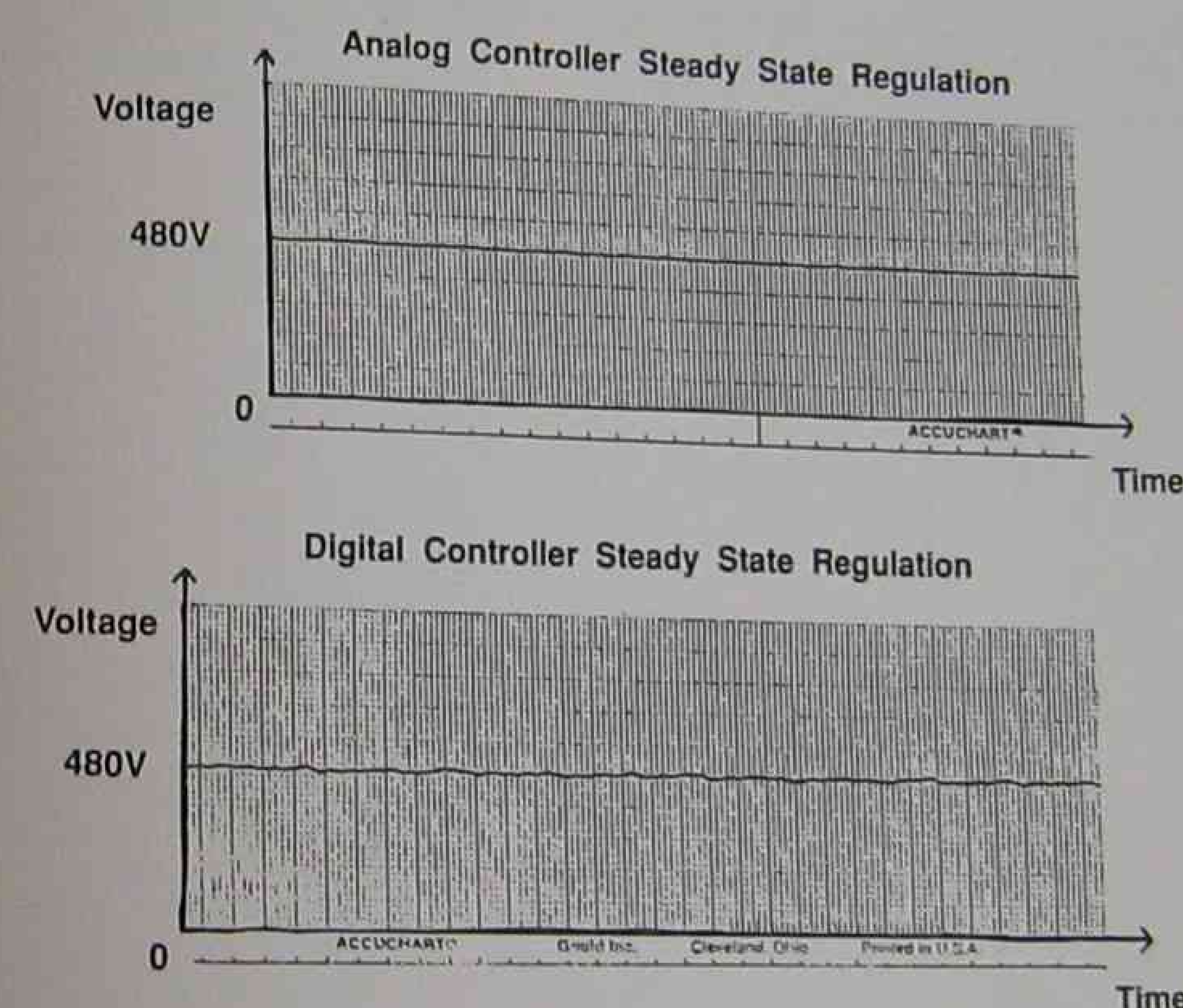


Figure 6. Analog and Digital Steady State Regulation Waveforms