2. The Transmitter

When you put simple things together, you get something complicated. When you put complicated things together, you get something that probably won't work.

There are those who believe, or at least hope, that their state-of-the-art microwave power tube, which they may have nursed through a costly and time-consuming development process, will come to them complete with a line cord that can be plugged into the wall so that they can be immediately "on the air." Unfortunately for many, this is far from the case.

A typical life-support system for a microwave power tube is called a transmitter and is shown in the block diagram of Fig. 2-1. Not all transmitters require all of the equipment that fills all of the blocks. Each functional block, however, must be evaluated to make sure that every function called out has been satisfied or is not needed. Often, multiple functions can be satisfied by the same subsystem.

2.1 High-power microwave tube

To transmitter designers, a microwave tube is reducible to an electrical load (or loads) to the power-conditioning systems and a thermal load to the cooling system. Once the load requirements have been satisfied and radio-frequency (RF) input has been applied, there is not much that the transmitter designer can do if RF output does not appear.

The microwave tube depicted, a klystron, presents the most rudimentary of all loads to the high-voltage system. Its "body," which comprises the anode and all of the RF internal circuits, is grounded for the well-being of all concerned because the RF input and output connections are made to it. The spent-beam collector can be at body potential, or it can consist of one or many separate stages that are insulated from the body and operated at voltages negative with respect to ground. This is called "depressed-collector" operation. Because the anode is grounded, the cathode must also be operated at a voltage that is negative with respect to ground. As we will see later, this negative cathode voltage may be as great as several hundred thousand volts, either continuously applied or in the form of single-event or time-repetitive pulses. In either case, the klystron, regardless of its size and expense, will behave as a thermionic diode in the space-charge-limited regime, where the current through it will be proportional to the voltage across it, raised to the 3/2 power (Child's law). The diode portion of the

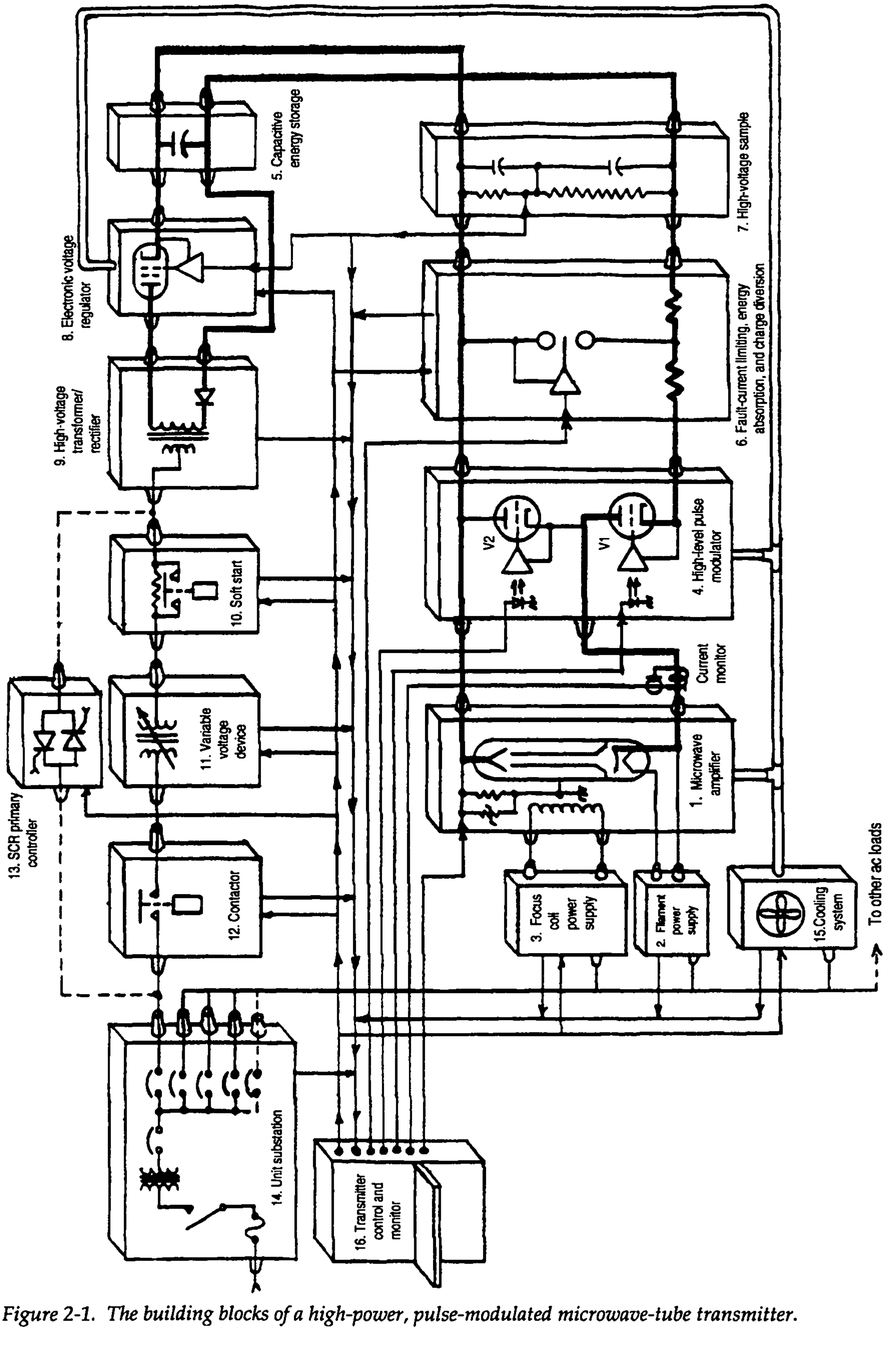

Figure 2-1. The building blocks of a high-power, pulse-modulated microwave-tube transmitter.

microwave tube is referred to as an electron gun (or, as the French would have it, an electron "cannon"). It determines not only the magnitude of the beam current but the velocity of the individual electrons that make it up. Whereas the current varies as the 3/2 power of the diode voltage, the electron velocity varies as the 1/2 power. The total beam power will vary as the 5/2 power of voltage, and the beam impedance, which is the load impedance the microwave tube presents to the transmitter, varies as the 1/2 power of voltage.

As we will see later, not all electron guns are simple diodes. Some have insulated anodes called modulating anodes, while others have insulated focus electrodes that are normally near cathode potential, and some have grid structures that are physically and electrically close to the cathodes.

2.2 Filament supply

With the exception of a few exotic cold-cathode devices, electron emission from cathodes is thermionic, requiring that the cathode surface be heated to a temperature in the vicinity of 1000°C. Almost without exception, thermionic cathodes are of the unipotential type, which are indirectly heated (as a slice of bread is indirectly heated in a toaster, rather than by the flow of current directly through it).

The power input requirements of cathode heaters are not in themselves high technology. They usually require less than 1 kW at voltages less than 50 V, ac or dc. What makes the filament supply interesting is that one side of the heater is referenced to the cathode, which, as we remember, may be several hundred thousand volts negative with respect to ground, if for only the duration of a microsecond-long pulse.

2.3 Focus magnet supply

Almost all microwave tubes require a magnetic field of some sort to focus the electron beam in a linear-beam tube or to cause electron spokes to rotate in a crossed-field device. If the tube manufacturer has provided the magnetic circuit as an integral part of the tube—as with periodic-permanent-magnet focusing or even uniform-field permanent-magnet focusing (which is rare but not unheard of)—then this is a box the transmitter designer does not have to worry about, except to keep magnetic material a sufficient distance away from sensitive components. Small linear-beam tubes, such as helix traveling-wave tubes (TWTs), and virtually all crossed-field devices have integral permanent-magnet systems.

Other tubes derive their magnetic fields from solenoids, which are either integral to the tube (wrapped-on solenoid) or separate, where they usually play a role in the physical support of the tube. Energizing such solenoids is the responsibility of the transmitter designer. Single solenoids, such as the ones for millimeter–wave power tubes, can require as much as 10 kW input power. The power must be regulated in current because large variations in solenoid resistance can be expected between its cold and hot states. Some huge multi-cavity klystrons have as many as six or seven separate solenoids arrayed along the length of the electron-beam drift space. Each may require a separate supply with separate adjustment.

2.4 Pulse modulator

In many microwave tube applications there is no need for continuous RF output power. In most radar transmitter and particle-accelerator applications, for instance, RF output is required to be pulsed, so that RF output may last only a few microseconds and recur every few milliseconds. Even the longest pulses last but a small fraction of a second. The duty factor, or duty cycle, of such microwave tube operation may be a small fraction of 1% and is only rarely more than 10%.

Microwave tube power consumption and thermal management considerations dictate that there be some means of turning the electron beam on when RF output is required and turning it off when it isn't. In the case of the power oscillator, the most classic example of which is the magnetron, there is no alternative to turning the beam on and off, because the length of the electron beam pulse is, for all intents and purposes, the length of the RF pulse as well.

Performing the switch function is the role of the pulse modulator. Figure 2-1 shows the most complicated, or at least the most brutish, kind: the hard-tube, full-beam modulator. Vacuum tube *V1*, which can be physically and electrically very large, will have to pass all of the cathode current of the microwave tube during the pulse and block all of its cathode voltage between pulses. Another electronic switch, *V2*, also a vacuum tube, is not commonly used in the application shown but functions as an active pull-up, or "tail-biter," not unlike devices used in integrated-circuit computer-logic elements. Tube *V1* is the active pull-down and *V2* is the active pull-up. The pull-down may have to sink hundreds of amperes, and the pull-up may have to discharge stray capacitance by a hundred thousand volts or more.

Other types of modulators, as we will see, are appropriate for microwave tubes that have additional gun electrodes, such as the modulating-anode and the control-grid tubes.

2.5 Pulsed energy storage

The peak-pulse current in low-duty applications can be hundreds or even thousands of times as great as the average beam current. A practical transmitter, therefore, needs a means of storing energy that is slowly accumulated during the interpulse interval and then rapidly delivering it to the load during each pulse. Storage capacitance is invariably used for this purpose because the current through it can change instantaneously, whereas the voltage across it cannot. To prevent capacitor voltage from changing appreciably during a pulse, it may be necessary to store many times as much energy as is delivered to the load during each pulse (except for a special case, which we will investigate). Energy-storage capacitor banks that store as much as a megajoule of energy (the explosive equivalent of a half-pound of TNT) and several coulombs of charge (the equivalent of commonplace lightning discharges) are by no means uncommon. Many times the energy and charge required for normal single-pulse performance is customarily stored. But this presents a problem. If there should be a microwave tube malfunction in the form of an internal electron-gun arc—and in most cases this is a "when" rather than an "if" scenario—all of the stored energy could be dissipated in the arc, unless something is done about it.

2.6 Fault current limiting and charge diversion

Energy can only be dissipated in resistance. Fortunately, the resistance of an arc in a vacuum between copper electrodes, which is what we have in a microwave tube electron gun, is small and inversely proportional to the current through it, up to several thousand amperes of arc current. Therefore, external resistance, which is large with respect to the arc resistance but small compared to the ratio of normal pulse voltage to current, will limit arc current and dissipate all but a tiny fraction of the stored energy. Supplying this external resistance is not an option. You do not have a usable transmitter without it!

Often current-limiting resistance is all that is required to prevent tube damage resulting from internal high-voltage arcing. In other cases, where the microwave tube is deemed more fragile, a charge diverter, usually called an electronic crowbar, is used. (It is most often a nervous tube vendor who claims that the company's warranty will be void if your system does not have a crowbar to provide this safety feature. However, if your system does have a crowbar and the tube fails anyway, the self-interested vendor will most likely claim that your crowbar did not work.) As shown in Fig. 2-1, the crowbar is nothing more than a device that shunts the high-voltage system within microseconds of the detection of fault current in the microwave tube. This arc does not share the stored energy, but it does share the stored charge. The crowbar is connected to a tap on the total surge resistance. The resistance between the capacitor bank and the crowbar determines the current through the crowbar arc. The resistance between the crowbar and the microwave tube assures that the crowbar takes most of the current and charge by making the total impedance of the path through the faulted tube much greater than that through the fired crowbar.

2.7 Voltage sample

If for no other reason than to provide the control-and-monitor system a proportional sample of voltage, there will be a need for a voltage divider connected across the high-voltage bus. It may also be the source of an error signal for an electronic voltage regulator, in which case it often will include frequency-compensation components to improve its transient response and ripple suppression.

2.8 Electronic voltage regulator

In all precision transmitters (especially those using TWTs as RF amplifiers), some form of regulation of the dc high voltage will be required. In the type illustrated, the linear (variable resistance) electron tube regulator is the most precise and has the best transient response. It is also the most expensive and inefficient. If a voltage regulator is to be used, there are less expensive and more efficient alternatives, which will be discussed later. As we shall also see, there are situations when voltage regulation is required on the load side of the capacitor bank. In such cases, the regulator must handle the peak-pulse current instead of the time-averaged current while maintaining precise output voltage. The linear vacuum-tube regulator is mandatory for such service.

2.9 High-voltage transformer/rectifier

This block is the beginning of the high-voltage dc system and the end of the primary-power ac system. This is true even in the so-called dc-to-dc-converter power supplies because they have a self-generated ac link within them. In large power systems, the ac service is usually three-phase. The transformer part of the block steps up the primary ac and often converts it to 6-, 12-, or even 24-phase input to the high-voltage rectifier. A well-designed and executed high-voltage dc loop is referenced to ground at only one point: the body of the microwave vacuum tube. Such a high-voltage loop is like electrical code house wiring, except in reverse. House wiring comprises black (hot), white (neutral), and green (safety ground) conductors. The neutral is grounded only at the service entry and nowhere else throughout the house. The microwave-tube dc loop has the negative cathode-potential lead (black equivalent), which must be insulated for tens or even hundreds of thousands of volts from ground; the positive current-return lead (white equivalent), which is isolated from ground but needs to be insulated for only a few hundreds or thousands (transient) of volts; and the equivalent of the green wire, which is the grounding of the individual metal enclosures that house the transmitter equipment. Remember, ground is only ground when there is no current through it.

2.10 Step start (or soft start)

Given that an electrically large energy-storage capacitor bank is a requirement of a pulse-modulated, high-power system—especially if the duty factor is low (high peak-to-average ratio)—it is necessary to face the problem that the initially uncharged bank is a virtual short circuit for the system that electrically precedes it. Means must be provided to limit inrush of the charging current. The simplest form of such limiting is shown in Fig. 2-1: the step-start, which comprises resistance of high enough value to keep current within system rating, energy-handling capability equal to the eventual amount stored in the bank, and a relay that short-circuits it when the bank is fully charged. As resistance, it can be deployed on either the ac or dc side of the transformer/rectifier. If an electronic voltage regulator is used on the input side of the bank, it can be programmed in conductivity to perform the soft-start function. When deployed as shown on the ac side, the resistance can be supplanted by either series ac capacitance or line inductance to increase the ac system source impedance without power dissipation.

2.11 Variable voltage device

In most, if not all, transmitters, it is anywhere from comforting to essential to be able to vary the effective amplitude of the ac input to the high-voltage transformer/rectifier. This is a function that could be performed by the electronic regulator, except that it effectively varies the dc output instead of the ac input. (Unless it happens to be part of a switch-mode dc-to-dc converter, in which case it will vary the dc input to the internal ac generator before it reaches the transformer/rectifier.)

As we will see, the variable device can be as simple as the variable autotransformer, or "Variac" in the common parlance, or as complicated as a polyphase silicon-controlled-rectifier (SCR) primary controller. It can also serve the function of "soft-start," supplanting the "step-start" function, or it can even be a true high-voltage SCR acting directly in the dc link.

2.12 High-speed contactor or switch-gear

The term "high-speed contactor" is actually a misnomer in this application. What is required in this block is a high-speed disconnect. When the microwave tube internally arcs and/or the electronic crowbar fires, everything on the line side of them is short-circuited, just as if a physical crowbar had been thrown across the high-voltage dc. Short-circuit current, limited only by the internal impedances of the system (predominantly leakage inductances of the transformers), will flow until the circuit is broken by the action of the high-speed disconnect. Even then, current will not stop until the first current zero is reached after the line circuit is physically broken, because the contacts will arc across, even in vacuum. If a primary SCR controller is used for the variable-voltage function, it will double as a solid-state relay. The gating of the SCRs can be halted with electronic speed much faster than even the fastest electromechanical device. Even so, conduction will once again continue until the first current zero is reached. In a three-phase system, the longest interval between the earliest termination of gate drive and the next current zero is one-third cycle.

2.13 SCR primary controller

The SCR primary controller, or "light-dimmer," can be programmed to perform the functions of high-speed disconnect, output voltage variability, soft start, and even regulation of capacitor-bank dc voltage. Modern high-voltage dc systems increasingly tend to use them. As will be discussed, the SCR primary controller affects all of these functions through phase-controlled conduction in high-efficiency, true switch-mode fashion.

2.14 Unit substation

A unit substation indeed! No, I do not mean the type of electrical substation that is surrounded by a chain-link fence and danger signs and that might be found on the outskirts of town. But I do mean a miniature version of such an installation that performs the same basic functions: circuit protection and voltage reduction.

The first such function, working our way backwards from the transmitter as shown in Fig. 2-1, is carried out by the circuit breakers. A unit substation is designed to accommodate a breaker panel and is, in fact, the most convenient and logical place for one. The second function is to provide a step-down transformer to reduce the subtransmission-line voltage, which for older installations in the USA was likely to have been 4160 V and now 13,200 V. Common secondary voltages in substations are in the 400-600-V range, especially if a primary SCR controller is used with the high-voltage dc power supply. But note that if the average volt-ampere demand is in the MVA range, line currents can become so large that fault currents resulting from high-impedance faults can hardly be distinguished from normal full-load line currents. If there is not a sufficient ratio between the currents produced by high-impedance faults and normal load currents, circuit breakers will either not trip at all or will require too great a time interval to do so. The result is often an electrical fire, which will please no one. In such situations, a higher secondary voltage is called for (perhaps as great as the incoming subtransmission voltage) to proportionately lower normal line current and increase the fault/normal ratio. But if the substation transformer has unity turns ratio, you might ask why even bother with it. The answer has to do with the *other* rating of a circuit breaker.

We are all familiar with the primary rating of a circuit breaker. If, for instance, we plug too many hair dryers and popcorn poppers into a typical 15-A household outlet, the breaker is going to trip sooner or later—the tripping time will be inversely proportional to the overload ratio—when the total load current exceeds 15 A. Suppose, however, that instead of plugging in too many appliances we plug in a strip of copper, shorting the outlet and thus producing what is called a "bolted" fault. Now we have to worry about the other rating of the breaker, which is how much fault current it can be expected to break. This characteristic is called its interrupting rating. The household-service 15-A breaker may have an interrupting rating of 10,000 A. If the fault current is greater than that, the breaker will surely trip—sooner, rather than later—but it will *not* open the circuit. What assurance do we have that the impedance of the fault will limit the fault current to less than the breaker's interrupting rating? The answer is none. What *will* limit the fault current is the *source* impedance. But how do we know what the source impedance will be? We have now arrived at the least-understood, but perhaps most-important, function of our unit substation.

The substation's power transformer, if it is properly sized, will be matched to the maximum volt-ampere demand of the system (plus a modest safety factor added in for comfort). The internal impedance of this transformer consists, for the most part, of the leakage inductance between primary and secondary windings. Leakage inductance, then, is a measure of how much of the flux produced by the primary winding fails to link with the secondary winding. The value of the line-frequency reactance of this leakage inductance is between 5% and 10% of the load impedance at full rating and is typically greater than the resistive component of transformer impedance (so the resistance can be ignored). So secondary fault current, even into a zero-impedance fault, will be between 10 and 20 times the normal full-load current. Often the equivalent of a unit substation is already provided to you as part of the facilities of the physical plant in which the transmitter is installed. If so, the most important feature of the primary power provided, other than its adequacy to provide enough volt-amperes to run the transmitter, is its internal impedance, normalized to the load base. It is up to the designer to find out its internal impedance and to do something about it if there is a problem.

Finally, at the front end of the substation it is comforting to have a fused, load-break manual disconnect switch, which allows a positive, no-nonsense disconnect from the incoming primary power. Such a disconnect is an essential feature for transmitter maintenance.

2.15 Cooling system

It is by no means unheard of that the difference between a successful and unsuccessful transmitter design is the cooling system. Often too little attention is paid to the mundane act of cooling electronic components because it is not "high-tech," or at least does not appear to be. Unless they are 100% efficient, all active systems, electrical or mechanical, convert a portion of their input energy to heat. This heat will be dissipated, one way or another. The purpose of a well-designed cooling system is to remove this heat while keeping the temperature rise of the heat source within acceptable limits.

There are some obvious temperature benchmarks. Copper, for instance, melts at 1073°C. Therefore, it is a good idea to keep the inner surface of the microwave tube beam collector below this temperature. Silicon junctions have severely shortened life expectancies above 300°C. (In fact, MIL-HDBK-217, the reliability bible for military systems, does not accept a reliability prediction using its guidelines if the junction temperatures exceed 175°C.) All chemical reactions that govern the life span of many, if not all, electronic components are governed by the Arhenius equation, which states that the speed of the reaction is a log-normal function of the absolute temperature. The lifetime of silicon junctions, for instance, is halved for each 10°C increase in their temperature. The life expectancy of thermionic emitters in vacuum tubes is also a function of operating temperature. (But that problem is outside the function of a transmitter's cooling system because hot thermionic emitters are a necessary evil.)

Later, quantitative relationships in cooling systems will be discussed, but for now the cooling system is depicted as a closed-loop liquid system with a liquid-to-air heat exchanger. This is because water is the most effective coolant. Some high-power microwave tube manufacturers state their devices are designed to be cooled by conducting away their heat through ambient air. In these cases, be aware that what the tube is mounted to is expected to have the properties of an infinite heat sink (that is, it can conduct away an infinite amount of heat without itself rising in temperature).

2.16 Control and monitor

At last we have reached the nervous system of the transmitter, whose nerve endings are in the form of an array of sensors that sample conditions throughout the transmitter. These sensors include voltage dividers; current monitors; optical and acoustic sensors; temperature, pressure, and flow sensors; and even closed-circuit TV cameras. The control function, or brain, of the transmitter includes the operator, although modern high-power RF sources are less and less dependent on human intervention for their control and rely increasingly on computer-based industrial programmable logic control (PLC) systems. Such systems perform ladder-logic and provide, if you will, the hand-eye coordination needed to successfully operate the transmitter. They also create the computer-screen graphics that make up the operator-machine interface. These graphics are far more informative and interpretable than the pilot lights and analog meters that are still, unfortunately, more standard than not in the industry.

Yet any control system must have the electronic equivalent of a conditioned-reflex, or knee-jerk, reaction that can in emergencies bypass reasoned thinking or programmed logic in order to do the right thing, every time, as quickly as possible. There are situations where such quick reactions are required. One obvious example that we have discussed already is the firing of the electronic crowbar in response to the detection of a high-voltage arc in our high-power microwave tube. This must occur within a few microseconds. Another is the automatic interruption of the primary power to the high-voltage dc power supply. These circuits, then, must be hard-wired so that their logic is infallible. The PLC, in its own good time, may take note of these involuntary reactions, update the status graphics accordingly, and perform whatever subsidiary activities it has been programmed to do, including automatic reset and restart.