

# HIGH POWER VARIABLE ATTENUATORS FOR INDUSTRIAL MICROWAVE PROCESSING

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## Abstract

Microwave heating processes often place demands on equipment that are not easily met with conventional system configurations. Performance limitations of commonly available system components can result in undesirable process control behavior, including instability, inefficiency and limited dynamic range. High power variable attenuators are capable of resolving some of these difficulties. For example, the inherent output frequency shift of magnetrons as output power varies can result in microwave coupling instability when regulating the process temperature of low loss materials. Variable attenuators can be used to vary microwave power delivered to the process material while allowing the magnetron output power to remain constant, thereby maintaining constant output frequency and improving the stability of frequency sensitive processes. Variable attenuators function in similar ways to resolve other process control difficulties. Various examples of these devices in open and closed loop control processes are presented.

## Introduction

Industrial microwave heating systems generally consist of three basic elements: a source of microwave power, a system for power delivery and an applicator for heating the process material. The characteristics of the process and how the material to be heated interacts with microwave energy usually dictate the requirements of the microwave source and power delivery system. However, in some cases these requirements are not easily met in typical system configurations using commercially available equipment. In particular, inherent performance characteristics of microwave power generators can necessitate special configurations of waveguide components used in the microwave power delivery system.

The performance of industrial microwave generators can be characterized by three basic operating parameters related to output microwave power: frequency stability, waveform ripple and power level control range. Each of these parameters can have an effect on the overall performance of the heating process. While models are available to meet the process requirements of any one parameter, finding one whose performance characteristics are ideal in all three is difficult.

### ***Frequency Sensitivity of Heating Processes***

Most microwave processes involve the heating of materials characterized by their dielectric properties, specifically dielectric constant and loss factor. Materials having a low dielectric loss factor (often referred to as "low loss") absorb microwave power less easily than high loss materials. Similar difficulties arise when heating very small amounts of material regardless of their loss characteristics. These difficulties can be related to frequency sensitivity by describing the process load (material and applicator) as a circuit element in a microwave network having a resonant frequency. The quality factor, Q, of the circuit element is defined in terms of the amount of energy stored in and lost to the process load and related to frequency as

$$Q \equiv 2p \left( \frac{\text{energy stored}}{\text{energy dissipated / cycle}} \right) = w \left( \frac{\text{energy stored}}{\text{power dissipated}} \right) = \frac{\text{resonant frequency}}{\text{half - power bandwidth}} = \frac{f_r}{f_2 - f_1} \quad [1]$$

*Power dissipated* is the amount of power absorbed by the cavity walls and dielectric material, while *half-power bandwidth* is the range of frequency outside of which the power is dissipated by less than half (return loss is less than -3 dB) as shown in Figure 1. When heating a small and/or low loss load under high power the power dissipated may be low compared to the energy stored, thus increasing Q and reducing the half-power bandwidth.

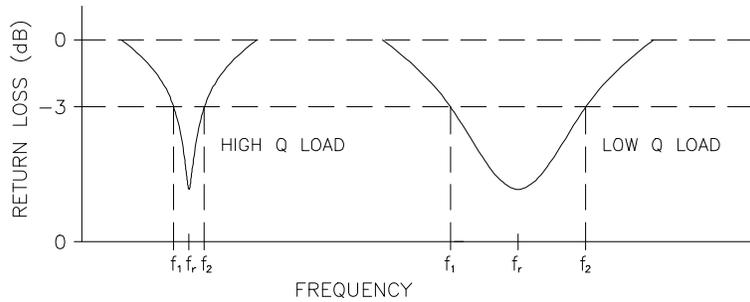


Figure 1, Comparative frequency response of low and high Q loads with respect to absorbed microwave power.

The consequence of a narrow half-power bandwidth becomes apparent when considering the output frequency of the microwave generator. Almost all microwave generators used in industrial microwave processing exhibit a characteristic inherent with continuous wave magnetrons used in these generators. Magnetrons operate at a frequency that varies with output power level, generally increasing as output power increases (Figure 2a). Typical processes can be very stable at any given frequency, but in some cases a change in output power level and the resulting shift in output frequency can cause reflected power to increase. This is particularly true if the frequency shift approaches the half-power bandwidth of the process load as shown in Figure 2b. A simple solution is to retune for the new operating frequency, but this may not be practical with some processes.

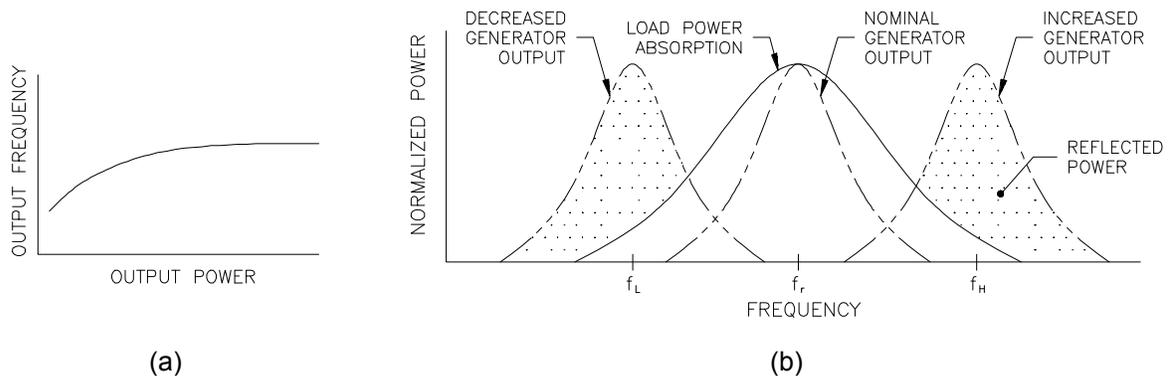


Figure 2, (a) Magnetron output frequency vs. output power level, (b) Reflected power due to output frequency shift.

**Process Sensitivity to Waveform Ripple**

Most microwave generators can be characterized as having one of three basic waveform types as illustrated in Figure 3. Many processes (e.g. heating of bulk materials) are not sensitive to the output waveform of the microwave generator, while some (e.g. diamond deposition) require very low waveform ripple. Generally, power supply designs that reduce the ripple can be prohibitively expensive, particularly at high output power levels.

In most power supply designs having medium ripple waveforms, the ripple amplitude remains constant as output power changes. Consequently, ripple amplitude as a percentage of output power varies with changes in power. For example, output waveform ripple that is 15% of output power at full power becomes roughly 30% at half power. The waveform ripple from a particular microwave generator may be acceptable at high power levels but unacceptable at lower power levels.

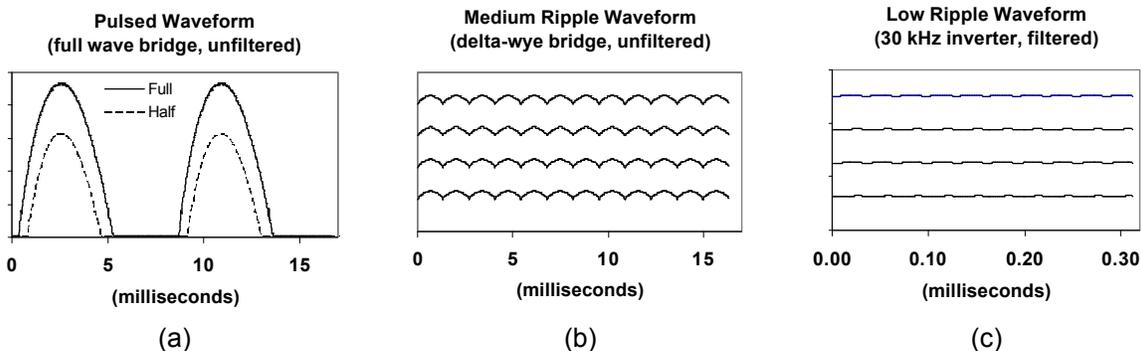


Figure 3, Typical output waveforms at various power levels from industrial microwave generators.

**Power Level Control Range**

Many commercially available variable output microwave generators designed for industrial heating applications employ switch mode (inverter) power supplies to drive the magnetron and control the output power level. Switch mode power supplies inherently require a nominal load for stable performance. Consequently, such microwave generators are not able to deliver stable power below a certain level, usually 10% of full output. For example, a microwave generator utilizing a switch mode power supply and rated for 3 kW output power can provide stable control down to approximately 300 W. Below this value the output becomes less stable or, with some models, a fault condition results that automatically shuts off microwave power.

**Variable Attenuators**

The microwave generator operating characteristics described above relating to output frequency and waveform ripple are due to varying the output power. Their detrimental effects on the heating process can be overcome by allowing the generator to remain in a steady state operating condition at a fixed output power level and varying the level of microwave power delivered to the process using a variable attenuator.

An attenuator can be somewhat loosely defined as any 2-port device that reduces the level of transmitted microwave power allowed to pass through by either reflecting or absorbing the power. Impedance matching devices (e.g. stub tuners) can be used as a reflective variable attenuator by varying the amount of reflected power in a controlled manner. While such devices are capable of high power operation, their use as attenuators may not provide stable operation as they can interact unpredictably with other impedance matching devices used for load impedance matching. For this reason, variable attenuators which absorb rather than reflect microwave power are preferred. In order to maximize the range of attenuation (ideally 0-100%), variable attenuators must be capable of absorbing all of the input power.

**Resistive Film Attenuators**

The most common type of waveguide variable attenuator is the rotary vane attenuator used for precision measurement applications. Rotary vane attenuators consist of a section of circular waveguide between two rectangular to circular waveguide transitions (Figure 4a). Within each section is a thin film of resistive material which crosses diametrically and, in the transition sections, perpendicular to the e-field. When all three resistive films are coplanar there is no induced electric current through them and thus no attenuation of the propagating field. Rotating the center section increases the induced electric current through its resistive film, thereby increasing attenuation. Maximum attenuation is reached when the angular displacement ( $F$ ) is 90 degrees.<sup>2</sup>

Another common type of absorptive attenuator uses a similar resistive material constructed as a blade and positioned to penetrate into the waveguide parallel to the electric fields (Figure 4b).<sup>3</sup> Attenuation is adjusted by varying the depth that the blade protrudes into the waveguide. As with rotary vane attenuators, heat dissipation from the lossy blade material is limited, thus making such devices unsuitable for high power applications.

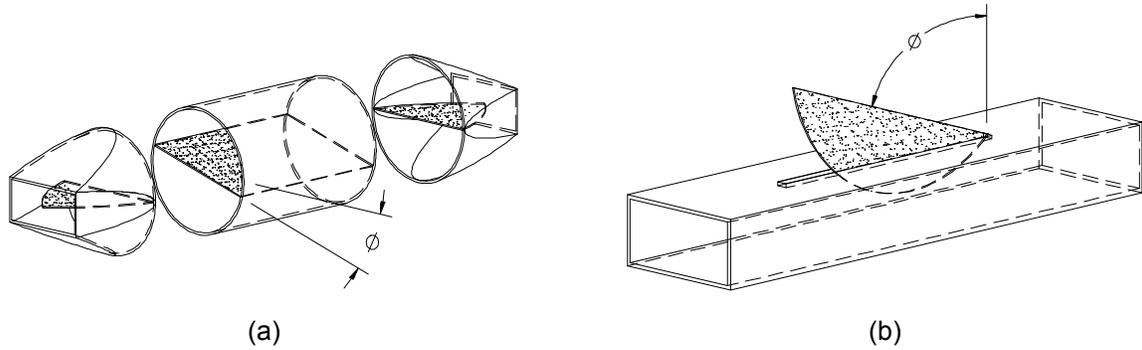


Figure 4, Resistive film type variable waveguide attenuators: (a) rotary vane and (b) protruding blade.

**Hybrid Attenuators**

In order to handle high power levels, absorptive (non-reflective) type attenuators utilize flowing water as the power absorbing element. Meredith<sup>4</sup> describes a method using -3 dB couplers, dummy loads and sliding short circuits (Figure 5). Although capable of very high power operation, this method may be impractical for many applications due to size and cost.

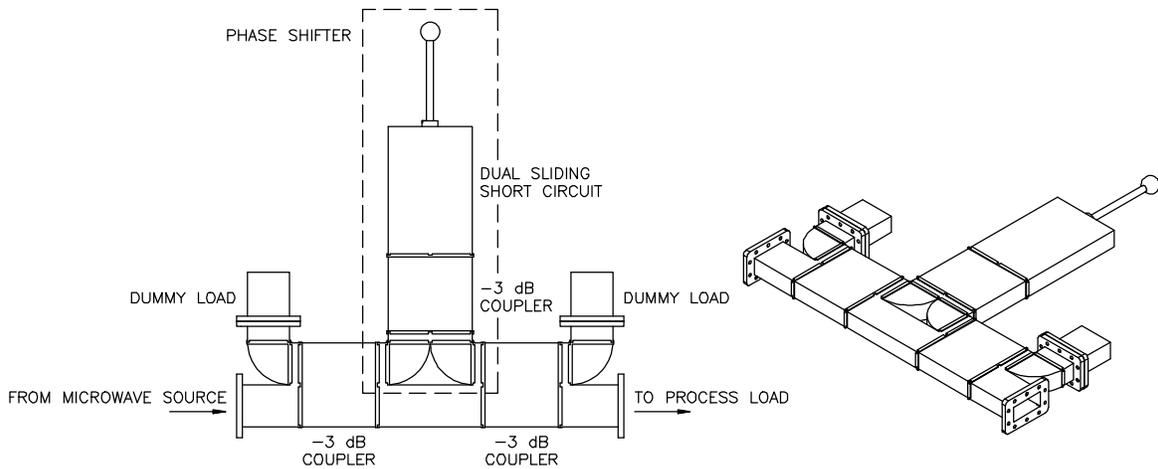


Figure 5, Hybrid variable attenuator utilizing short slot (-3 dB) sidewall couplers.

Another type of hybrid variable attenuator consists of three common waveguide components: 3-port circulator, adjustable tuning stub and dummy load (Figure 6). In this configuration transmitted microwave power enters the circulator and is directed to the port at which the dummy load and stub are connected. Ideally, when the stub is in the neutral (fully retracted) position all of the transmitted power is absorbed by the dummy load and none is delivered to the process load. In this case the attenuation is 100%. As the stub is adjusted from its neutral position microwave power is reflected back to the circulator where it is then directed to the process load. The position of the stub and the resulting reflection coefficient determine the net attenuation of transmitted power.

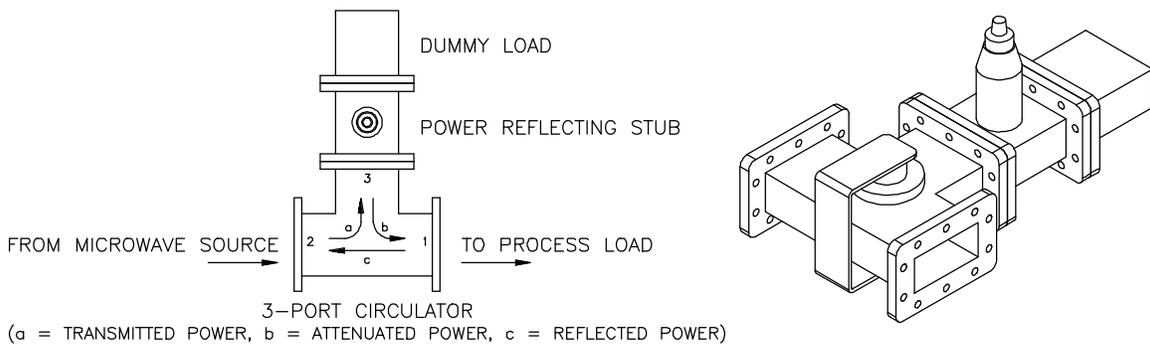


Figure 6, Hybrid variable attenuator utilizing a 3-port circulator, stub and load.

**System Configuration with a Variable Attenuator**

A simple waveguide system configuration utilizing a variable attenuator can be utilized for resolving the process performance limitations described earlier. Figure 7 illustrates a typical laboratory system for heating small loads. Although the variable attenuator utilizes a 3-port circulator and dummy load, two components commonly used together to serve as an isolator for protecting the microwave source (magnetron) from reflected power, the variable attenuator does not function as an isolator. A separate isolator must be provided if high reflected power due to load impedance mismatch is likely. In this case the variable attenuator is preferably located immediately after the isolator and before any devices associated with power measurement and impedance matching.

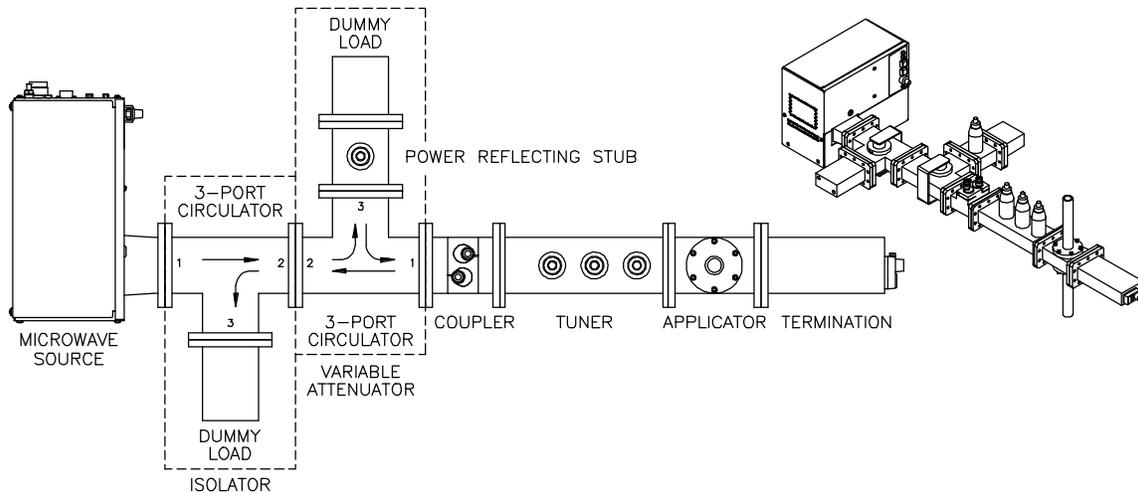


Figure 7, Typical microwave processing system utilizing a variable attenuator.

**Variable Power with Constant Frequency**

As described earlier, process loads that are small and/or have a low dielectric loss factor may be sufficiently frequency sensitive such that adjusting the microwave generator output power level can result in unstable heating. With a system that includes a variable attenuator as in Figure 7, the microwave generator can be set to a nominal fixed output power level while the variable attenuator is used to adjust

power delivered to the load. Ideally the generator should be set to just above the maximum power level required by the process, thus minimizing wasted energy.

Controlling delivered microwave power using a variable attenuator is much the same as controlling the output of the microwave generator directly. Manual control is done simply by adjusting the position of the power reflecting device by hand, while automated control is possible by motorizing the adjustment mechanism. Close loop process control is configured by delivering the output control signal from the process controller to the motor controller (Figure 8).

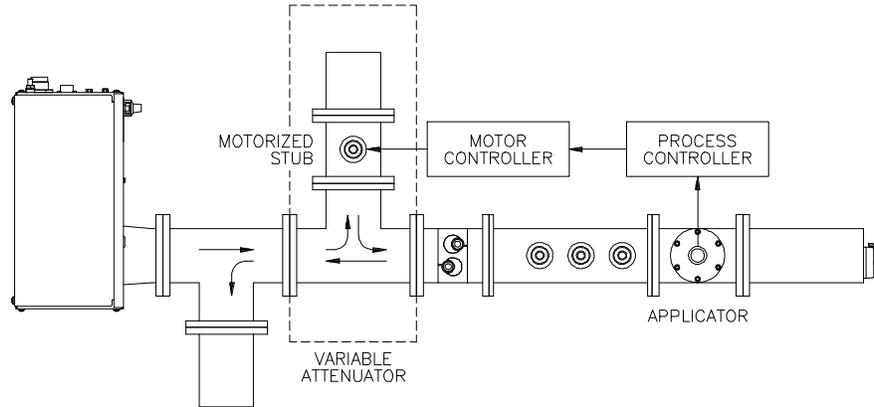


Figure 8, Closed loop process control utilizing a motorized variable attenuator.

**Minimizing Waveform Ripple**

The method described above for constant frequency operation is also beneficial in cases where waveform ripple must be minimized throughout the range of delivered microwave power. By maintaining the microwave generator output power level at maximum and varying delivered power using the variable attenuator, the ripple amplitude will remain a fixed percentage of delivered power.

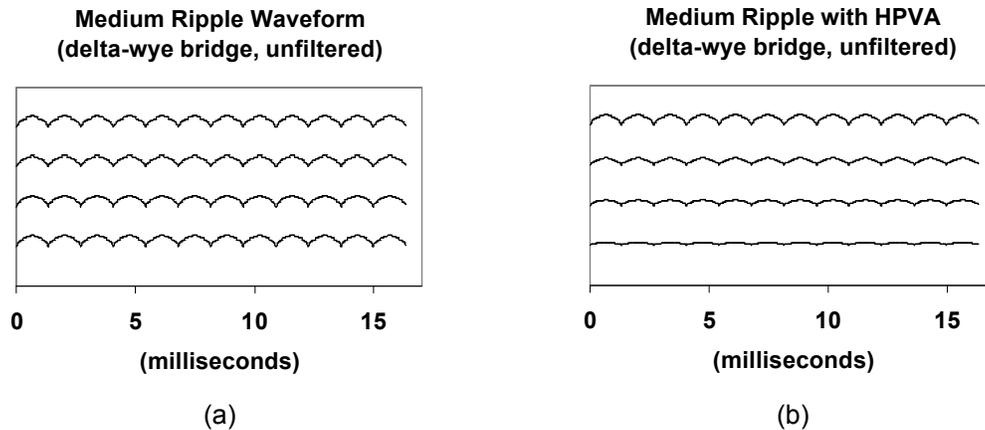


Figure 9, Medium ripple waveforms at various power levels by adjusting (a) transmitted power and (b) attenuated power.

**Extending the Microwave Power Control Range**

As described earlier, many commercially available microwave generators do not operate stably at output power levels below 10% of full output. A variable attenuator can be used to extend the microwave power control range to well below this 10% lower limit. Figure 10 shows how the control range varies with

different fixed settings of the variable attenuator. For example, when 75% of the transmitted microwave power is attenuated, the low end of the power control range of a 3kW generator is reduced from 300 Watts to 75 Watts.

Delivered power can be controlled either by the microwave generator while the attenuator setting remains fixed, as in the above example, or by the variable attenuator while the level of generated power remains fixed. For example, as shown in Figure 11, the same 3kW generator can be used to deliver power down to nearly zero using the variable attenuator for power control.

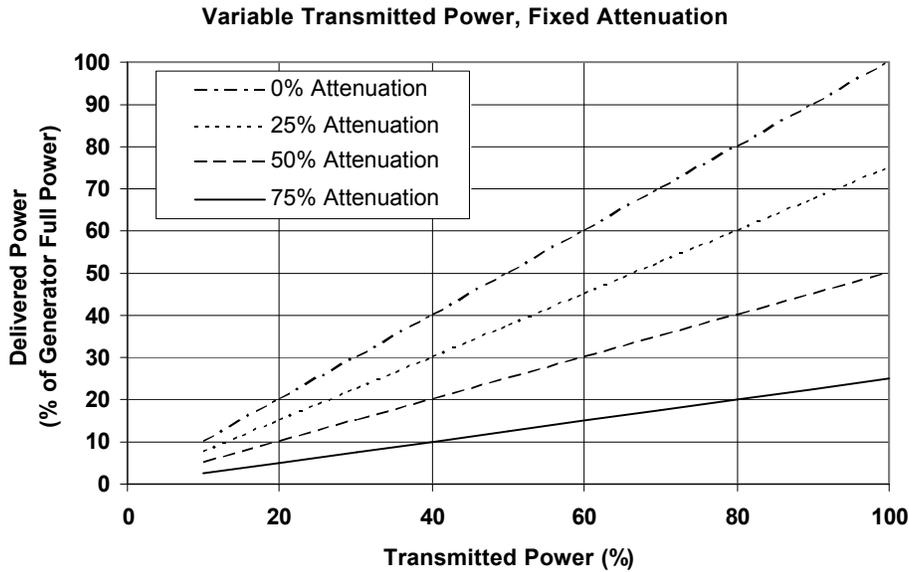


Figure 10, Delivered microwave power with variable transmitted power at various fixed levels of attenuation.

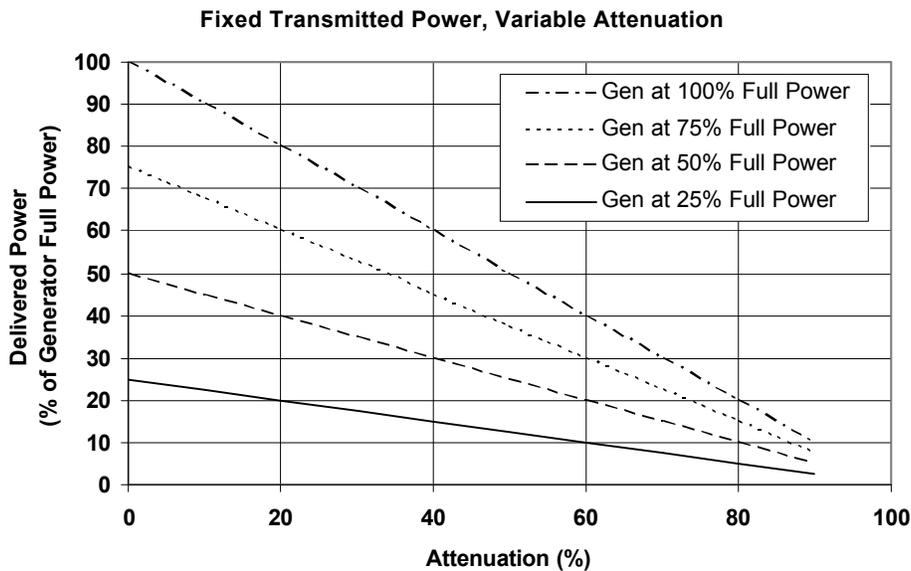


Figure 11, Delivered microwave power with variable attenuation at various fixed levels of transmitted power.

Whether to control delivered power by adjusting transmitted power or attenuated power depends on process requirements as discussed earlier. In some cases, however, controlling delivered power by adjusting both may be necessary. For example, the dynamic range of delivered power in an automated (closed loop control) process may extend from the full output of the microwave generator to less than its 10% lower limit.

The scheme illustrated in Figure 12 utilizes a signal processor to determine the optimal settings of the two controlled devices according to the signal received from the process controller. A simplified algorithm might establish a minimum setpoint for the microwave generator (e.g. 20% of full output), above which only the generator is controlled while the variable attenuator remains set at zero attenuation. Control of the variable attenuator begins when the required delivered power is below the minimum generator setpoint.

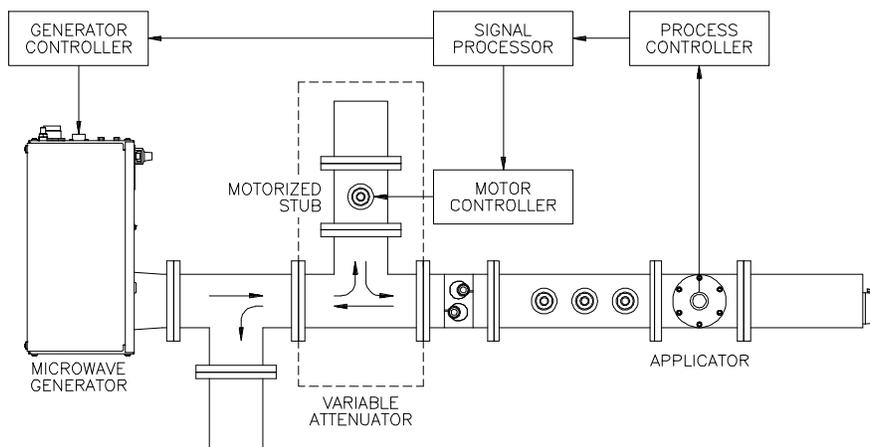


Figure 12, Simplified closed loop process control scheme for simultaneous control of the microwave generator and variable attenuator.

### Summary

High power variable attenuators are useful in industrial microwave heating applications where process stability is compromised by inherent operating characteristics and limitations of commercially available microwave generators. Process performance can be enhanced by allowing the microwave generator to remain in a steady state operating condition while controlling microwave power delivered to the process load using a variable attenuator. Variable attenuators can be constructed using standard waveguide components and manually controlled or automated for closed loop process control.

### References

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- <sup>2</sup> Engen, Glenn F., "Microwave Circuit Theory and Foundations of Microwave Metrology," page 81, IET, 1992.
- <sup>3</sup> "Model 375A Variable Attenuators," Hewlett Packard operating note # 00219-6, April, 1968.
- <sup>4</sup> R.J. Meredith, "Microwave Transmission: Theory and Practice"; pp. 146 in *Engineers' Handbook of Industrial Microwave Heating*, The Institute of Electrical Engineers, London, 1998.