APPLICATION NOTE

MICROWAVE HEATING APPLICATIONS
PART 3: SWITCH-MODE RESONANT POWER SUPPLIES FOR MICROWAVE GENERATORS

PROBLEM

Microwave technology can be advantageous for industrial scale heating, provided that the application benefits from the unique aspects of microwave heating as compared with conventional heating. In this series of Applications Notes, we describe a set of relatively simple considerations that aid the non-specialists in assessing whether microwave technology may be advantageously employed in a particular heating application. The first Application Note in this series [1] detailed some of the fundamental and unique characteristics of microwave heating, and discussed factors that need to be considered when choosing between microwave and conventional heating approaches.

The second Application Note [2] detailed some of the considerations necessary when designing the equipment and process for a particular heating application. This Application Note discusses the specifics surrounding advanced microwave power supplies.

BACKGROUND

Microwave Generator Efficiency

Microwave generators have the following components:

- Magnetron
- Power Supply
- Waveguide Launcher
- Applicator

Each of these components exhibits a specific efficiency, defined as the ratio between input and output power. Table 1 presents efficiencies for the generator components in a typical low power microwave generator. Since cumulative efficiencies in a system are the product of individual component efficiencies, it can be seen from the table that microwave generator efficiencies typically range between 52% and 63%, depending on the application.

Component	Min	Max	Remark
Magnetron Power Supply	85%		Domestic, 1400 W
		95%	Industrial, 3000 W
Magnetron	68%		1000 W, air cooled
		72%	3000 W, water cooled
Waveguide Launcher & Cavity		95%	Well-tuned cavity, good load
	90%		Large cavity, variable product
Total Efficiency	52%	63%	

Table 1 - Component efficiencies in a microwave generator

Microwave generator efficiencies can be improved; however, improvements are not possible in all components. Magnetron designs are essentially fixed by physical laws that make 2450 MHz systems less efficient than 915 MHz systems. Thus, the microwave generators in household and small industrial applications (<3 kW) exhibit efficiencies of up to 63%, (Table 1), while those designed to deliver 50 kW or more of microwave power have been reported to operate at up to 85% efficiency.

The components in microwave subsystems, the microwave power supply, the magnetron, the waveguide and the applicator cavity, are the focus of most efforts to improve microwave generator efficiency. Only modest reductions in losses — for example, from 10% down to 5% — are possible through more efficient applicator cavities design (obtained through the use of electromagnetic simulations). This leaves modifications to the microwave power supply as the primary candidate for redesign for improved efficiency.

Microwave Power Supply

Microwave power supplies provide a constant, stable current at a specified working voltage to the magnetron in the microwave generator; the power supply is considered a constant current generator (Figure 1), independent from main line fluctuation and load changes. Improvements to magnetron power supply efficiencies have been and continue to be the primary manufacturers' focus for global efficiency gains. To date, these gains have been driven by steady progress in the design of electronic components.

The voltage of a magnetron is fixed and therefore the power of the magnetron is linear and proportional to the current supplied. The terms "current" and "power" are thus synonymous in this instance. The working voltage of a magnetron is called the "trigger voltage" since the magnetron only produces microwave energy at its antenna when the voltage is above this threshold. Magnetron voltage is a direct voltage, in the range of 4 kV for magnetrons rated up to 3 kW, 7 to 8 kV for 6 kW magnetrons, and 16 kV and over for magnetrons rated above 50 kW. In operation, the magnetron voltage drops approximately 5% from its nominal value, within the first few minutes. As a consequence, at constant current, the magnetron power decreases by the same percentage until the voltage has stabilized.

Microwave power supplies are divided into two families: those operating with a constant and fixed current; and those operating with a constant, but adjustable current. Fixed current power supplies typically find application in non-complex systems, where simple ON/OFF control of the microwave power can be used without risk; this is the most common solution used for control in domestic microwave ovens. The term "power control" in these power supplies refers to the fact that the average power is controlled by varying the ratio between the ON and OFF cycle; i.e., when half power is selected, the power supply ON time (usually some seconds) is exactly equal to the OFF time. So-called saturating-transformer power supplies are an example of such a low-cost, simple ON/OFF topology. These power supplies suffer from the fact that they have a very limited ability to deal with magnetron malfunctions such as overvoltage and overcurrent (on the high voltage side) due to magnetron moding or arcing. As well, they are both large and heavy.

Figure 1 - 3 kW Resonant Magnetron Power Supply (CR 840)

Power supplies with current that is continuously adjustable over the entire range manage the current using a low voltage reference signal, i.e., 0-10 V. Most modern generators of this type control the current supplied to the magnetron, usually referred as "anodic current", as the real electrical power, adjusting the current whenever the voltage varies. The reference signal sets the real power, not just the anodic current.

Such adjustable power supplies can be divided in two sub-categories: those working at main line frequency (50 or 60 Hz), known as "linear" power supplies, and those operating as switch-mode power supplies that "switch" at a high frequency (>20 kHz) the energy they deliver and supply the magnetron with a direct current. Linear power supplies control the output power, "cutting" the phase of the supplied current; typically, they are relatively simple and incapable of dynamic performance.

Industry is moving away from using linear supplies, adopting more modern adjustable power supplies that generally employ switching technology.

SOLUTION

Switch-Mode Power Supplies

Switching power supplies, while complex, offer superior performances over linear fixed or linear variable power supplies (see Table 2). Performance advantages include:

- More stable output power in the presence of a large fluctuation of the main line.
- More stable output power in the presence of load variations.
- Reduction in stored energy; this characteristic permits fast control of overvoltage and overcurrent conditions in the magnetron, providing excellent protection for both magnetron and power supply.
- Increased magnetron life (by a factor of 2-3), under the same working conditions, when using models with a low output ripple value, like a typical switch-mode unit.

Recently, high-frequency converters have been developed that are capable of supplying the anode EHT (extra-high-voltage) of high-power magnetrons. These systems have switching frequencies up to 100 kHz and this enables very rapid control of EHT and the ability to switch off the supply in tenths of microseconds. This latter characteristic is critical for limiting the energy dissipated within the magnetron under fault conditions. Fault energy in these switching power supplies is reduced by three-orders-of-magnitude as compared with traditional saturating transformer designs.

Although advantageous in terms of minimal fault energy dissipation, high frequency switching can cause an increase in switching losses that must be considered when choosing one of these power supplies.

Resonant Converter Topologies

A resonant converter processes power in a sinusoidal manner and the switching devices are softly commutated. Resonant converters have the following general advantages:

- The voltage across the switch drops to zero before the switch turns on (ZVS = zero voltage switching).
- There is no overlap area between V and I when turning ON.
- Capacitive losses are eliminated.

A number of different resonant converter topologies are available, each with its own unique set of advantages and drawbacks.

Series Resonant (SR) Converter

Advantages:

- Reduced switching losses and EMI through ZVS: improved efficiency.
- Reduced magnetic components size due to high frequency operation.

Drawbacks:

- Performance can be optimized at a single operating point, but without a wide range of input voltage and load variations.
- The output cannot be regulated under load condition.
- Pulsating rectifier current (capacitor output): limitation for high output current application.

Performance Comparison of Linear vs. Switch-Mode

	Linear	Switch-Mode
Stability vs. Main Line	±3% with main line fluctuations up to ±10%	±0.1% with main line fluctuations up to ±10%
Stability vs. Magnetron Change	The power supplied is proportional to the magnetron voltage ±5%	The power supplied is constant
Stored Energy (Joule) in Inductor (L) and Capacitor (C)	1,1 J (L) + 2 J (C) = 3,1 J	0,011 J (L) + 0,027 J (C) = 0,038 J
Typical Switch-OFF Time	10-20 msec	1 msec
Magnetron Life	6.000 h (Type YJ1600)	25.000 h (Type YJ1600)

Table 2 - The performance characteristics of linear vs. switch-mode magnetron power supplies

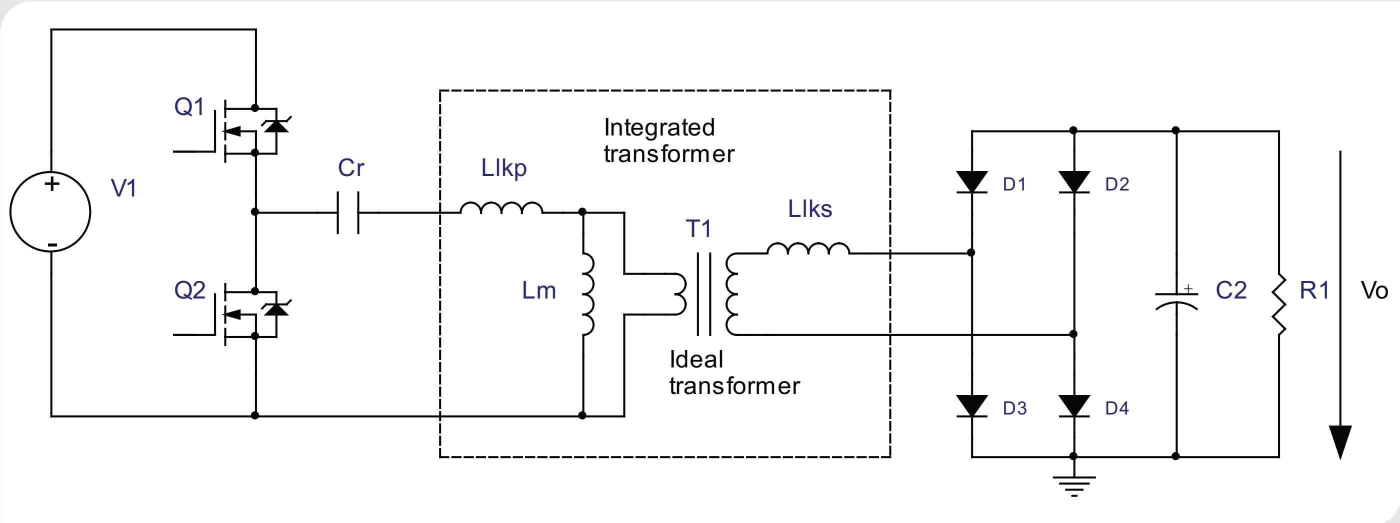

Figure 2 - Schematic layout of an LLC resonant converter, where R1 represent the magnetron load

Parallel Resonant (PR) Converter

Advantages:

- Output can be regulated under no load condition.
- Continuous rectifier current (inductor output); suitable for high output current application.

Drawbacks:

- The primary side current is almost independent of load condition; significant current may circulate through the resonant network, even under the no load condition.
- The circulating current increases as the input voltage increases, limiting the range of input voltages.

LLC Resonant Converter

The topology of an LLC resonant converter (Figure 2) is nearly the same as that of a conventional LC series resonant converter with the primary difference being that the magnetizing inductance (Lm) of the transformer is relatively small and involved in the resonance operation. LLC resonant converters can survive heavy fault situations such as a transformer short-circuit or a burned output rectifier stage.

LLC resonant converters are somewhat more complex since they require a specialized transformer design in which two magnetic components are implemented with a single core (using the primary side leakage Llkp inductance as a resonant inductor), thus saving on magnetic components (Lr). Leakage inductance not only exists in the primary side but also in the secondary side, (Llks), and it is necessary to consider the leakage inductance in the secondary side. Where possible, all of the magnetic components are embedded in the same device, using gapped ferrite cores or distributed air gap cores.

Using the LLC resonant converter topology, a 3 kW power supply can power a 2 kW magnetron, in a power range of 20%-100%. The CR 840 unit in Figure 1 has a complete set of alarm-condition sensing. Input line is 400V, 3-phase, and the primary current of the filament transformer is controlled by the power supply, by an internal CPU. The unit has a volume of 10 dm^3, which may be compared with the volume of a traditional saturating-transformer at near 25 dm^3 (a 40% reduction). The weight is only 8 kg, a 75% reduction when compared to a traditional converter weighing 35 kg.

CONCLUSION

Microwave generators are made up of a magnetron, a waveguide/launcher and the power supply. Manufacturers of the most energy efficient microwave generators focus on efficiency gains that can be achieved in the microwave power supply, since gains are limited in the other components. Most modern power supplies have a switched mode electronic topology which exhibit improved efficiencies along with a variety of other advantages such as light weight, compact, and safer operations.

Resonant cavity switch mode converters are advanced designs for switch mode power supplies, with LLC resonant converters being the most advanced design of this family. MKS has developed an efficient 3 kW LLC resonant cavity power supply that can power a 2 kW magnetron. The CR 840 unit in Figure 1 has a complete set of alarm-condition sensing.

References

[1] MKS Instruments Inc. Applications Note: "Microwave Heating Applications Part 1: Fundamentals"

[2] MKS Instruments Inc. Applications Note: "Microwave Heating Applications Part 2: Process and Equipment Issues"