Short Papers

A Method for the 2.45-GHz Magnetron Output Power Control

Diana Martin, Angela Jianu, and Daniel Ighigeanu

***Abstract*—A new method that overcomes the disadvantages of the conventional magnetron output power (MOP) control is presented in this paper. The conventional *LC* single-phase half-wave doubler supply has been modified in order to allow the use of a manually controlled and/or PC-controlled electronic variator. Trains of high-voltage pulses followed by inhibited high-voltage pulses are periodically applied on the magnetron anode yielding a corresponding variation of the average MOP, with programmed steps, maintaining the advantage of peak microwave output power operation. The PC-controlled system provides a practically continuous variation of the magnetron average output power.**

***Index Terms*—Anode current, electronic variator, magnetron, power control, pulsed microwave.**

I. Introduction

Magnetron output power (MOP) is proportional to average operational anode current. Variable MOP is typically accomplished by one of the following current control methods (CCMs): control of the average anode current by duty cycle variation (CCM1), control of peak anode current by power supply (CCM2) and, for magnetrons with electromagnets, control of the anode current by magnetic field variation (CCM3).

CCM1 requires magnetron operation at varying duty cycles. Periods of operation at high peak power levels are followed by long periods (seconds) of no power, rendering this approach unacceptable for certain applications. In chemical synthesis, for example, samples could "cool" drastically between switching steps of seconds [1].

CCM2 provides continuous output power variation by control of magnetron peak anode current (MHC). However, this method is not applicable for microorganisms sterilization where pulse modulated microwaves are required because higher electric fields accelerate death rate more than continuous waves [2], [3]. It is important to use microwave power at high peak level while increasing the material temperature as little as possible in order to point out whether the microwave nonthermal effect exists or not.

In order to overcome the disadvantages of CCM1 and CCM2, when applied to chemical synthesis or microorganisms sterilization, a modified variant of CCM1, referred here as MCCM1 (modified CCM1), has been developed.

II. Method and Results

The conventional operation mode of magnetrons supplied by an *LC* single-phase half doubler (LCHWD) is a pulsed one: microwave power (MWP) is generated as 10-ms pulses at 50-Hz repetition rate by applying high-voltage pulses (AHV) of 10-ms duration and 50-Hz repetition rate ($R_{\rm AHV}$) on the magnetron anode.

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The proposed method (MCCM1) uses a magnetron supply of LCHWD type modified as shown in the block diagram of the magnetron power control system (MPCS) represented in Fig. 1 (manual control) and Fig. 2 (PC-based control). The main power units consisting of a high-voltage diode (HVD), a high-voltage capacitor (HVC), and a high-voltage anode transformer (HVAT) are similar to the units used for the conventional magnetron energization system. The difference consists in the use of a separate transformer for the filament supply (HVFT) and of an electronic variator (EV) added to the HVAT primary circuit. The main component of EV control system is the phase converter, which modifies EV conduction angle by controlling the input voltage level by means of a potentiometer (manual regime) or by a D/A converter (PC-controlled regime).

The principle of the proposed control method is illustrated in Fig. 3, which shows the MWP and AHV waveforms for the following situations: no anode high-voltage pulse inhibition occurs [see Fig. 3(a)], one applied anode high-voltage pulse followed by one inhibited pulse [see Fig. 3(b)], and N applied high-voltage pulses followed by one inhibited high-voltage pulse [see Fig. 3(c)].

The corresponding variation of the MOP is given by the following equation:

$$MWP = MWP_{\rm avgm} \cdot N/(N+K) \tag{1}$$

where

$MWP_{\rm avgm}$ maximum average MWP (half of the peak microwave power generated by the magnetron in the classical operation mode);

N number of high-voltage pulses applied on the magnetron anode;

K number of the inhibited high-voltage pulses.

By means of the control system shown in Fig. 1, manual control has first been implemented on a domestic microwave oven that allowed the inhibition of 0–16 anode high-voltage pulses, rendering a corresponding anode high-voltage pulse repetition rate of 50–3.125 Hz, respectively.

Fig. 4 shows the real waveforms of the anode peak current pulses (Wave A) and anode high-voltage pulses (Wave B) obtained by testing the control method on a 850-W maxim output power domestic microwave oven.

Fig. 4(a) is an illustration of conventional operation: oscillograms of the anode peak current pulses and anode high-voltage pulses of 10-ms duration applied on the magnetron anode when no anode high-voltage pulse inhibition is commanded ($K = 0$, pulse repetition rate 50 Hz, inter-pulse duration 20 ms, mean anode current 170 mA, and mean output power 460 W).

Fig. 4(b) and (c) illustrates the anode high-voltage on/off control for two cases: (b) $N = 1$ and $K = 1$, pulse repetition rate 25 Hz, inter-pulse duration 40 ms, mean anode current 80 mA and mean output power 220 W and (c) $N = 1$ and $K = 3$, pulse repetition rate 12.5 Hz, inter-pulse duration 80 ms, mean anode current 40 mA, and mean output power 110 W.

In accordance with the method principle, switching the work regime from the conventional "50-Hz" one to the "25-Hz" one, by means of the control system shown in Fig. 1, should keep peak anode current constant. Still, the "25-Hz" work regime showed a slightly smaller value for peak anode current. By further decreasing the work frequency, peak

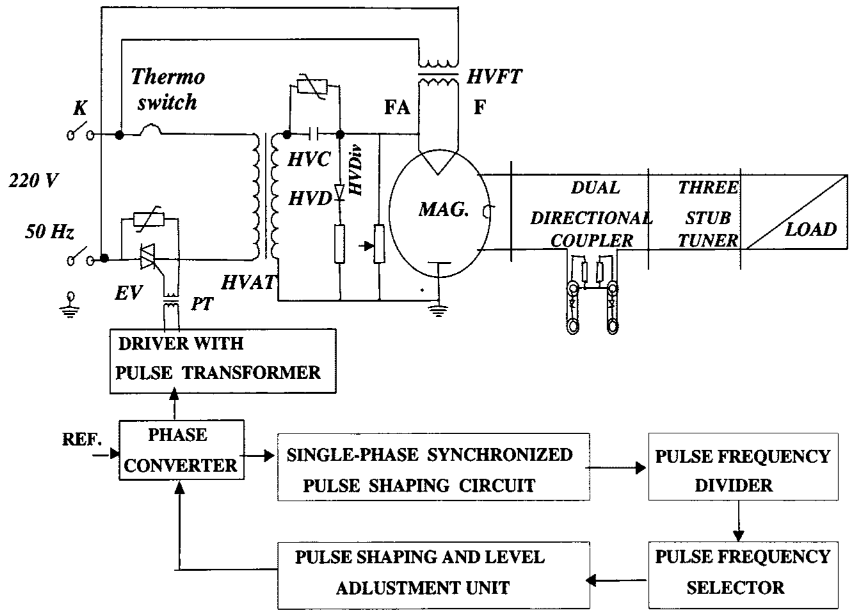


Fig. 1. Block diagram of the manual control system.

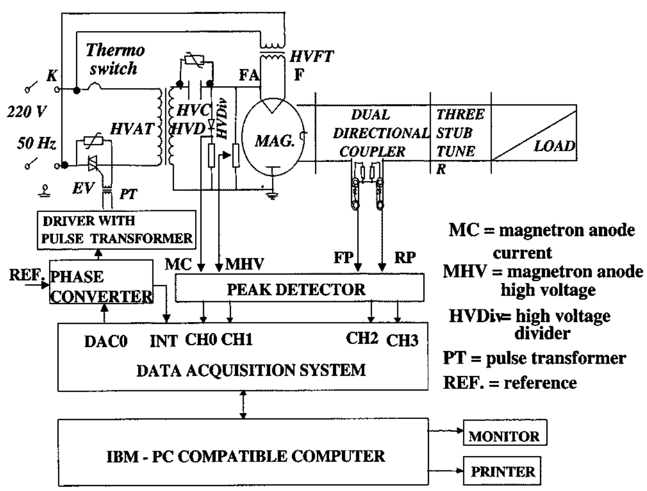


Fig. 2. Block diagram of the PC-based control system.

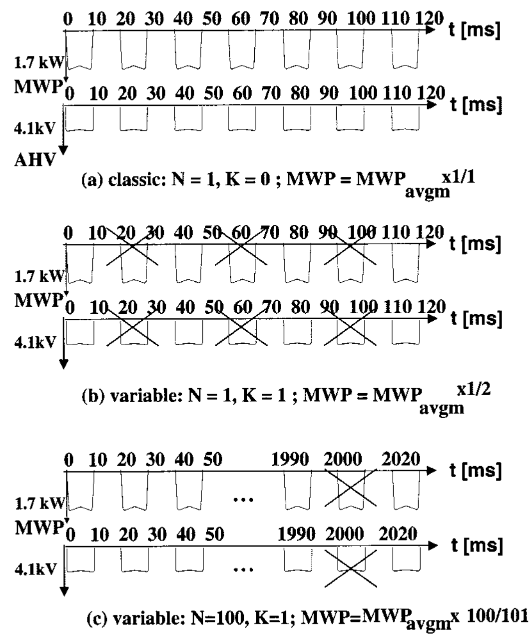


Fig. 3. Representation of the control method principle. (a) Conventional operation (no anode high-voltage pulse inhibition). (b)–(c) Anode high-voltage pulse inhibition occurs.

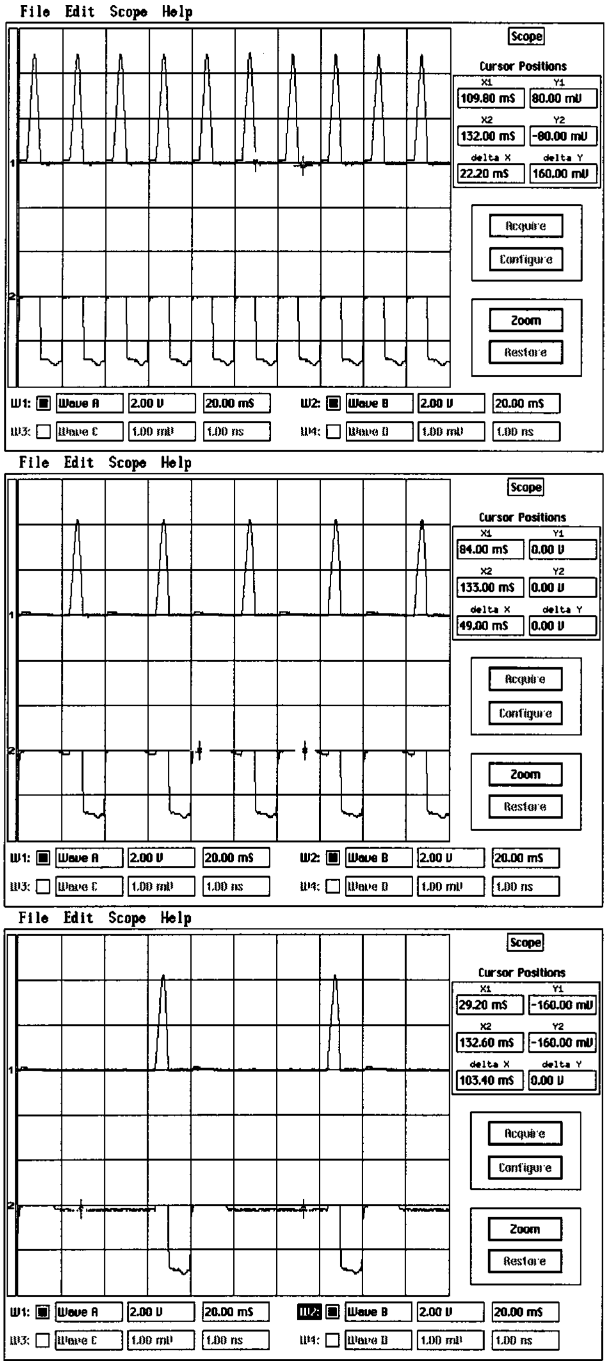
anode current remained constant, as it should have for the whole frequency range (from 25 to 3.125 Hz). A possible explanation is a small synchronization error (synchronization is done with the ac supply). This error can be easily eliminated by the PC-based control method, by controlling the thyristor conduction angle in order to keep peak current constant with varying frequency.

When implemented by a PC-controlled system (Fig. 2), the proposed MOP control method provides a practically continuous variation of the magnetron average output power (similar to CCM2), maintaining the advantage of operating the magnetron at peak microwave output power (similar to CCM1). Depending on the process, when using PC-based control, the values for N and K may be programmed and controlled to obtain very small variation steps for MWP.

The following values for N and K were used during testing with PC-based control: $N = 1 \div 100$, $K = 0 \div 5$. A corresponding variation of the MOP, with programmed small steps (up to 0.01 $MWP_{\rm avgm}$), in the range $MWP_{\rm avgm}(K = 0) \div 0.16 MWP_{\rm avgm}$ ($K = 5$ and $N = 1$) was yielded in accordance with (1).

The proposed control method (MCCM1) in both implementations (manual control and PC-based control) has been used in parallel with classical control methods (CCM1 and CCM2) in order to ensure maximum flexibility for the power control system of the 2.45-GHz commercial magnetron supplied by a modified *LC* single-phase half-wave doubler.

Signals proportional to magnetron peak anode voltage (MHV), MC, peak forward microwave power (FP) and peak reflected microwave power (RF) (Fig. 2) are monitored by an electronic system (four peak detectors and data acquisition system) and further processed by an IBM-compatible PC unit. The operator may choose the CCM (CCM1, CCM2 or MCCM1) and set the following magnetron control system



(a)

(b)

(c)

Fig. 4. Real waveforms for anode peak current (Wave A) and anode high voltage (Wave B) for: (a) conventional operation and (b)–(c) anode high-voltage on/off control operation. (a) Average anode current $= 170$ mA, $N = 1$, and $K = 0$ (no anode high-voltage pulse inhibition), pulse repetition rate $= 50$ Hz. (b) Average anode current $= 80$ mA, $N = 1$, and $K = 1$ (one applied anode high-voltage pulse followed by one inhibited pulse), pulse repetition rate $= 25$ Hz. (c) Average anode current $= 40$ mA, $N = 1$, and $K = 3$ (one applied anode high-voltage pulse followed by three anode inhibited pulses), pulse repetition rate $= 12.5$ Hz.

parameters: peak anode current level, RF limit, average anode current limit, peak anode voltage limit.

In order to protect the magnetron and power supply, the reflected power level, average anode current level, and peak anode voltage level are constantly monitored and compared with preset limits, corresponding to magnetron and power supply ratings.

To avoid the use of an isolator, which would increase the system cost, the RF (which may cause magnetron overheating and moding leading to premature failure) is continuously tested and compared with the preprogrammed limit. The control is very sensitive to this condition and reacts immediately within the next half-cycle by reducing the EV conduction angle. A quench period can be set from one to more full cycles and it is immediately followed by a new test of the RF. If the reflected power remains above the programmed limit, a complete interruption of the voltage applied on the magnetron anode occurs. Power is also shut off if the programmed limits of the average anode current and peak anode voltage are exceeded.

PC-based control is used in parallel with classical control so that the magnetron operating regime characteristics are set by the following two means: 1) digital control on the MPCS front panel (potentiometer for the MWP adjustment and holding at the desired level; digital selector switches for the selection of the operating mode—CCM1, CCM2 or MCCM1) and 2) PC software.

Various conventional protective devices such as thermal switches and over-current relays were used (supplementary to the programmed operating limits) to protect the magnetron and power supply. The control is, therefore, sufficiently flexible to meet any operating situation.

A set of experiments has been performed with MPCS properly programmed under each application requirements. Our major research objects were focused on the use of microwave irradiation to enhance the reaction rate in chemical synthesis, to reduce the duration and temperature increase in microorganisms sterilization processes, as well as to reduce the power consumption during the nitrogen oxides and sulfur dioxide removal process.

The experiments were performed using a multimode rectangular cavity (MRC) of 450 mm $\times$ 245 mm $\times$ 245 mm inner dimensions, excited by a slotted waveguide antenna. A structure based on five inclined series slots cut at $\lambda_g/2$ apart in the broad wall of a WR430 waveguide has been used as slotted waveguide. The above-described antenna type was chosen due to its recognized property to introduce the microwave energy into a microwave cavity over a wide area with high transfer efficiency and good energy uniformity. It is easy to manufacture and convenient to operate.

Preliminary results showed that microorganisms death rate increased from 50% to 90% when using pulse modulated microwaves instead of continuous microwaves at the same temperature. The experiments concerning the pollutants removal from the flue gases demonstrated that pulse modulated microwaves were more efficient, of about 20%–30% than continuous microwaves at the same average microwave power. This results in a considerable reduction of power and, therefore, costs.

III. Conclusions

The proposed MOP control method (MCCM1) combines the advantages of both conventional current-control methods: MOP control by variation of the duty cycles and MOP control by variation of the peak values. MCCM1 provides a practically continuous variation of the magnetron average output power, also maintaining the advantage of operation at peak microwave output power. MCCM1 can be applied for material processing by microwave irradiation. The method reliability will be further tested under different conditions.

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Time-Varying Volterra-Series Analysis of Spectral Regrowth and Noise Power Ratio in FET Mixers

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***Abstract*—This paper presents a direct and robust analysis technique for evaluating nonlinear distortion phenomena in FET mixers excited by multitone signals. Time-varying Volterra-series analysis has previously been proven to be appropriate for small-signal intermodulation-distortion calculations in mixers excited by simple RF signals. Spectral convolutions of the suitably mapped control voltages are introduced in this paper in order to solve the nonlinear current source calculations for narrow-band modulated or broad-band multicarrier RF signals. Simulations and measurements of a properly characterized resistive mixer validate the accuracy of this direct and noniterative analysis tool for spectral regrowth and noise-power-ratio prediction in such applications.**

***Index Terms*—Intermodulation distortion, MESFETs, mixers, Volterra series.**

I. Introduction

The complex nature of the nonlinear distortion phenomena appearing in microwave applications, when excited by multitone signals, has determined an increased use of new characterization procedures instead of the classical two-tone intermodulation distortion (IMD) test. In this sense, the adjacent channel power ratio (ACPR) is being widely employed for evaluating the broadening of a signal bandwidth (spectral regrowth) and the distortion caused in the neighbor signals. The noise power ratio (NPR) is, however, preferred to quantify the total co-channel distortion appearing in a particular frequency band of a multicarrier signal.

In amplifiers, this problem has recently been considered making use of low-frequency transformations [1], transient envelope analysis [2], Volterra series [3], or spectral balance [4]. However, very few results have been reported for other applications [5], and the mixer case is as yet unsolved. For small-signal RF excitations, the case of most practical significance in mixers, time-varying Volterra-series analysis has been proven to constitute an accurate and simple tool for IMD calculations [6]. Nevertheless, and to the authors' knowledge, most published works in FET mixers have dealt with simple (one- or two-tone) RF signals [7], [8].

In this paper, we propose a technique to extend this powerful nonlinear analysis method to the handling of more complex excitation signals at circuit level. In an analogous way to [3], it is assumed that the circuit is weakly nonlinear for the RF signal such that a time-varying Taylor-series expansion of the device's nonlinearities up to the third degree is adequate. The accuracy of our approach is validated comparing measured and simulated values in a resistive mixer in a previously unpublished way.

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II. Time-Varying Volterra Analysis

The time-varying Volterra-series or large-signal/small-signal technique [9] begins by first analyzing the nonlinear circuit under large-signal excitation (LO), employing, for instance, the well-known harmonic-balance method. The nonlinear circuit components are then replaced by time-varying elements, and the small-signal nonlinear current technique of Volterra-series applied.

In Fig. 1, we show the general topology of a single FET mixer for applying the above technique. In active gate or drain mixers, $V_{\mathrm{RF}} = V\mathrm{g}$ represents the RF signal, a role played by $V\mathrm{d}$ if it is resistive. The circuit has been divided into a linear subcircuit where the elements have been represented by their conversion matrices, and the nonlinear current sources ($I\mathrm{gs}_i^{\mathrm{NL}}$, $I\mathrm{gd}_i^{\mathrm{NL}}$, and $I\mathrm{ds}_i^{\mathrm{NL}}$) determined by the ith degree Taylor expansion terms ($i > 1$) for each respective nonlinearity. The subindex c indicates the conversion matrix for the corresponding time-varying element, Ω and "1" represent the frequency diagonal and identity matrices [9]. Impedance matrices are used for the inductances, while the admittance ones describe the capacitances.

Solving the linear subcircuit to obtain the first-order control voltages and the first-order parameters (conversion loss or gain, RF input impedance, and IF output impedance) for a discrete multitone excitation, or a discretized continuous spectrum, does not differ in principle from the classical one- or two-tone case. The conversion matrices should be evaluated, and the circuit solved for each excitation frequency component.

The problem arises when the nonlinear current sources have to be evaluated. To illustrate this situation, we will consider the second-order nonlinear current source for the predominant nonlinearity $I\mathrm{ds}(V\mathrm{gs}, V\mathrm{ds})$, whose Taylor-series expansion is represented in the following:

$$\begin{aligned} I\mathrm{ds}(V\mathrm{gs}, V\mathrm{ds}) = {} & I\mathrm{ds}(V_{\mathrm{GS}}, V_{\mathrm{DS}}) + Gm1 \cdot v\mathrm{gs} + Gds \cdot v\mathrm{ds} \\ & + Gm2 \cdot v\mathrm{gs}^2 + Gmd \cdot v\mathrm{gs} \cdot v\mathrm{ds} + Gd2 \cdot v\mathrm{ds}^2 \\ & + Gm3 \cdot v\mathrm{gs}^3 + Gm2d \cdot v\mathrm{gs}^2 \cdot v\mathrm{ds} \\ & + Gmd2 \cdot v\mathrm{gs} \cdot v\mathrm{ds}^2 + Gd3 \cdot v\mathrm{ds}^3. \end{aligned} \tag{1}$$

From the first-order calculation, we can obtain a set of first-order control voltages $V\mathrm{gs}_1$ and $V\mathrm{ds}_1$. Each control voltage vector would be of the form

$$V\mathrm{gs}_1(\Omega_k) = \begin{bmatrix} V\mathrm{gs}_1^{-N}(N \cdot \omega_{\mathrm{LO}} - \omega_k)^* \\ \vdots \\ V\mathrm{gs}_1^{-1}(\omega_{\mathrm{LO}} - \omega_k)^* \\ V\mathrm{gs}_1^{0}(\omega_k) \\ V\mathrm{gs}_1^{1}(\omega_{\mathrm{LO}} + \omega_k) \\ \vdots \\ V\mathrm{gs}_1^{N}(N \cdot \omega_{\mathrm{LO}} + \omega_k) \end{bmatrix},$$

$$\text{with } \omega_k = |\omega_{\mathrm{LO}} - \omega_{\mathrm{RF}_k}| \quad \text{and } k = 1, \cdots, K. \tag{2}$$