Parametric Design Guidelines for MW Oven Inverter

C.Bocchiola; International Rectifier Corporation,

Via Trieste 25, 27100 Pavia(Italy) ; e-mail : cbocchi1@irf.com

Topics : Power Electronic topologies; Microwave oven; energy saving

Abstract

Today's Microwave ovens are often equipped with inverterized MW generators; compared with old style appliances, the magnetron is no more driven by a bulky ferro-resonant power supply, but by an electronic inverter, lighter, more efficient and, moreover, able to modulate the MW power, at least to a certain extent. The electronic power supply is generally designed around a resonant inverter which drives an HV transformer, followed by a voltage multiplying rectifier, needed to provide the 4-6kV DC requested by the magnetron. Single ended parallel resonant inverter is often a good choice, at least for MW ovens fed by 115V line. Being such topology also used for low cost induction heating hobs, it could appear similar design process may be applied; unfortunately, the presence of the HV transformer and of the voltage multiplier changes a lot the way the converter operates, and a revised design procedure needs to be developed. In this paper, parametric design analysis for single ended converter aimed to MW ovens is presented, and results compared with Pspice® simulation and practical measurements on a commercially available magnetron inverter.

Inverterized Magnetron Power Supply

Figure 1 is a sketch of a typical magnetron used in MW oven appliances; also, a typical schematic of its power supply is shown. The single ended parallel resonant converter uses HV transformer leakage inductance and primary resonant capacitor to generate resonant waveforms across the primary of the HV transformer. To limit the isolation requirements of the HV trafo, its secondary side usually provides half the voltage needed to polarize the magnetron, and a diode/capacitor voltage doubler configuration is then needed to develop the 4-6kVdc requested by the RF tube.

Converter Parametric Analysis

While the behavior of the single ended converter is well known, the combination of such converter with the HV transformer and the voltage doubler poses some challenges when parametric design is attempted. Generally speaking there are 3 constraints which have to be respected:

a) The power to be delivered to the load
b) The maximum Vce/Ice allowed by the power switch
c) The need to maintain ZVS turn-on

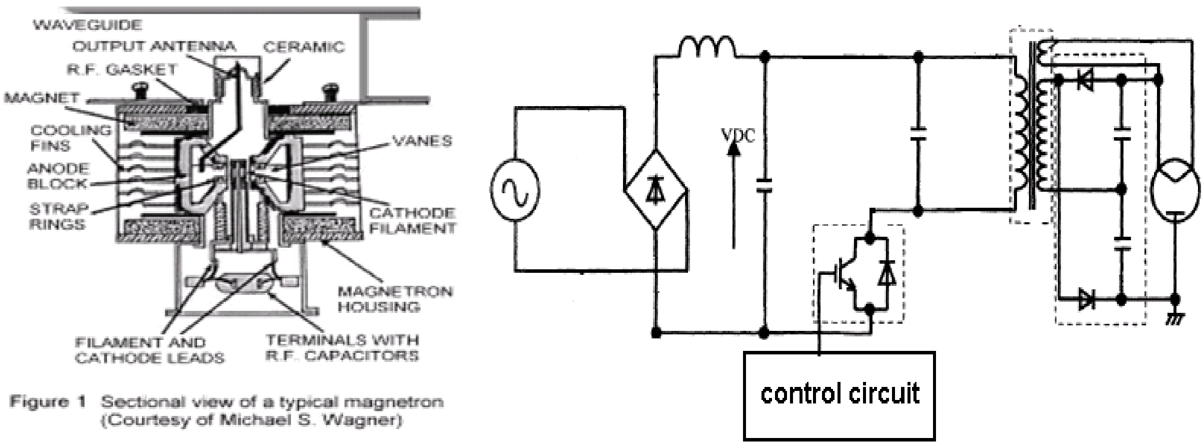


Figure 1: Magnetron sketch and inverter tolology.

In the case of MWO, a general model of the converter is shown in Fig. 2, and constitutes the basis for the following discussion.

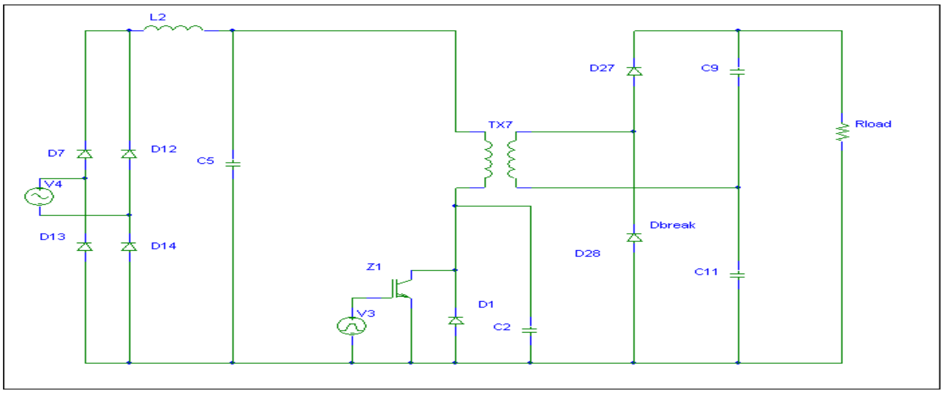


Figure 2: General model for the converter

Parametric design needs the output stage (HV trafo and voltage doubler) being modeled so that they appear on the primary side as a R_L network. Then, the design of the converter can be done as for the induction heating application. But, the operation of the inverter is NOT symmetric. In fact, by Fig 2 and assuming the HV trafo is not inverting, said Ton and Toff the ON and OFF times of the switch Z1, during Ton the voltage applied at the primary is Vin, while capacitor C9 is re-charged; during Toff, voltage at the transformer primary is Vce(t)-Vin, while capacitor C11 is re-charged. The average voltages across C11 and C9 are not equal to each other. As a “very first” approximation, we can say that V(C11) and V(C9) stay in a ratio which is function of Vcepk and Vin, Ton and Toff. More precisely :

$$V(C9)ave = V(C11)ave * Vin/(Vcepk-Vin) * Ton/Toff$$

The approximation comes by the fact the voltage drop on the HV trafo secondary leakage inductance is neglected, and such voltage drop is different between Ton and Toff as the recharge current is different. If C9 and C11 have a value which stays in the same ratio as their peak voltage, then also their voltage ripple will be similar. We also need to consider that, to avoid adding an external inductor on the primary side, the resonating inductor is achieved by ad hoc increasing leakage inductance of the trafo (see Fig.3).

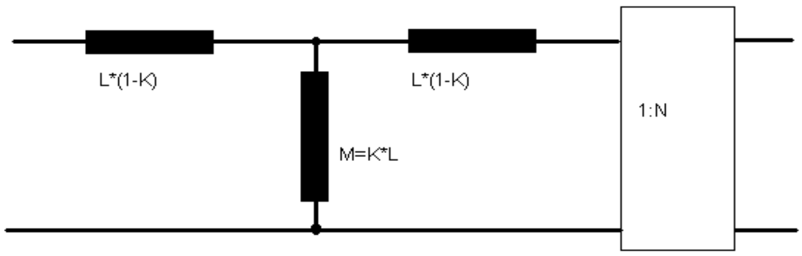


Figure 3: HV transformer primary side model

To complete the converter model, the “equivalent” load is needed. Because of the effect of the voltage doubler, the reflected load on the primary side of the HV trafo, should be Rload/4. Actually, because the voltages across C9 and C11 are not equal, “different” loads are reflected at the input of the voltage multiplier, and so different damping of the primary resonant circuit occur during Ton and Toff. A detailed analysis is very complex; in line of principle, the equivalent resistances at the input of the multiplier are different between each other and are between RL/4 and RL/8. It is now possible to calculate the total impedances at the transformer primary, which are in the form:

$$Zon_{N,j} := s \cdot L_j \cdot (1-K) + \frac{\left[s^2 \cdot K \cdot (1-K) \cdot \left(L_j\right)^2 + s \cdot K \cdot L_j \cdot \frac{Ron}{N^2}\right]}{s \cdot L_j + \frac{Ron}{N^2}} \qquad [1]$$

$$Zoff_{N,j} := s \cdot L_j \cdot (1-K) + \frac{\left[s^2 \cdot K \cdot (1-K) \cdot \left(L_j\right)^2 + s \cdot K \cdot L_j \cdot \frac{Roff}{N^2}\right]}{s \cdot L_j + \frac{Roff}{N^2}} \qquad [1bis]$$

Finally, we need to consider the effect of the secondary leakage inductance at the output of the HV trafo; this will generate a “voltage drop” such that Vo (peak value) will be different from Vcepk * N (where N=N1 is the transformer turn ratio). By keeping this into account, Vopk is given by:

$$Vopkest := \frac{Vin \cdot K \cdot \frac{Ron}{N1}}{\left| s \cdot L_{j1} \cdot \left(1-K^2\right) + \frac{Ron}{N1^2} \right|} + \frac{K \cdot \frac{Roff}{N1} \cdot (Vcepk - Vin)}{\left| s \cdot L_{j1} \cdot \left(1-K^2\right) + \frac{Roff}{N1^2} \right|} \qquad [2]$$

Where, again, different damping between Ton and Toff is allowed for. The set of equations derived in the previous discussion are the basis for the proposed design procedure, as it will be shown in the following. First of all, we need to decide which parameters are a priori given and which need to be calculated. In our approach, only 5 parameters are given: Vo, Po, Vin(pk), Fsw and Vcepk. Now, load resistance is simply derived by:

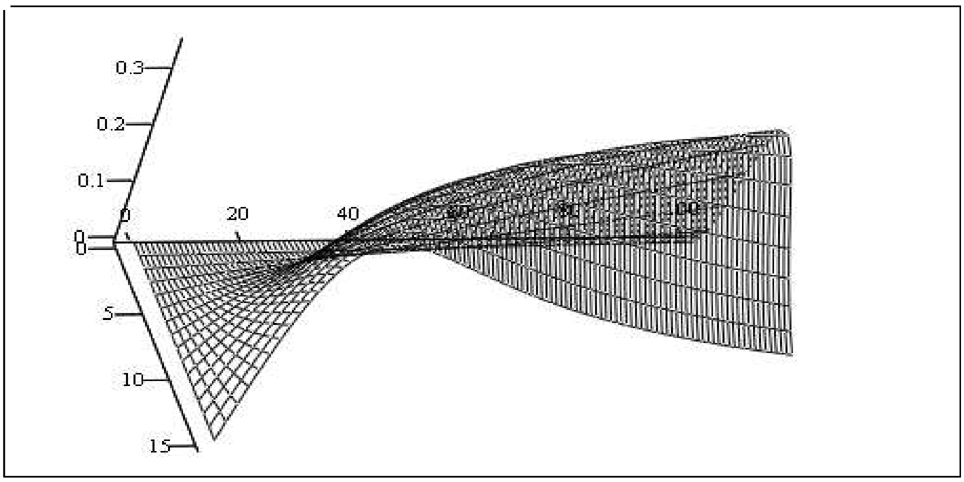
$$Rload := \frac{Vopk^2}{Popk} \qquad [3]$$

While, having specified Vcepk and Fsw, Toff and Ton follow:

$$Toff := \frac{\pi}{Fsw \cdot \left(\frac{Vcepk}{Vin} + \pi \right)} \qquad [4]$$

$$Ton := \frac{1}{Fsw} - Toff \qquad [4bis]$$

Toff equation is approximated; damping is not taken into account. On the other side, damping could NOT be introduced yet because the HV trafo has still to be designed yet and reflection ratio between its secondary and primary side is not known! Coupling factor for the HV trafo needs to be selected. All the design equations are too much inter-dependent between each other and some parameter needs to be fixed… based on the designer’s experience. We have chosen to impose a reasonable K value. At this point, L and N are the only two still unknown parameters, and two independent constraints are necessary. The approach is the following: drawing the 3D graph of Zon (Zoff) versus L and N, we get the picture of Fig. 4. Actually, what is represented here is the ratio between the real and imaginary part of Zon(Zoff).



RatioOn

Figure 4: design optimization surface

The locus where the ratio is maximum, give the points L-N1 which maximize the power transfer. Because Zon may differ from Zoff, there will be two solutions… and an average has to be chosen. Please remember this is a design guideline, not a complete and precise analytical design tool. Once a solution has been chosen, L and N1 are known, and Cres can be calculated as:

$$\mathrm{Cres} := \frac{\mathrm{Toff}^2}{\left(\pi^2 \cdot \mathrm{Lpoff}_{N1,\,j1}\right) \cdot \left(\frac{\mathrm{Vcepk}}{\mathrm{Vcepk} - \mathrm{Vin}}\right)^2} \qquad [5]$$

Now all the design parameters are known. Vopk can be checked by means of Eq [2], while peak power is given by:

$$\mathrm{Ploadpk} := \frac{\mathrm{Vin}^2 \cdot \mathrm{Fsw}}{\mathrm{Rpon}_{N1,\,j1}} \cdot \left[\mathrm{Ton} + \tau s \cdot \left(-1.5 + 2 \cdot \exp\left(\frac{-\mathrm{Ton}}{\tau s}\right) - 0.5 \cdot \exp\left(-2 \cdot \frac{\mathrm{Ton}}{\tau s}\right)\right)\right] + \frac{\mathrm{Fsw} \cdot \mathrm{Rpoff}_{N1,\,j1} \cdot \mathrm{Toff}}{8} \cdot \mathrm{deltaI}^2$$

Where

$$\mathrm{deltaI} := \frac{\mathrm{Vin}}{\mathrm{Rpon}_{N1,\,j1}} \cdot \left(1 - \exp\left(\frac{-\mathrm{Ton}}{\tau s}\right)\right)$$

And

$$\tau s := \frac{\mathrm{Lpon}_{N1,\,j1}}{\mathrm{Rpon}_{N1,\,j1}}$$

In the above eq. N1 is the value of N chosen by Fig 4, and j1 is the index for L. Lpon and Lpoff, as well as Rpon and Rpoff, are the L-R value reflected on the HV trafo primary side, during Ton and Toff. The MWO converter has been thus simplified to a single ended parallel resonant converter where the resonating components are Lpon (and Lpoff) and Cres, and the damping is given by Rpon (and Rpoff).

Design Example, simulation and measurement verification

In the following example, the known parameters were:

RF power : 900W

Estimated magnetron efficiency : 55%

Switching frequency : 40kHz

Peak input voltage : 165V

Peak primary switch voltage : 600V

From the curve of Fig 4 (re-calculated), optimal turn ratio and leakage inductance are derived:

N1 = 15 ; Lleak = 30uH

Then, Cres = 390pF, Vopk = 4450V, Ploadpk = 2300W and Icepk = 73A

The same design is simulated by using spice. The ripple is almost equivalent, and the sum of the peak voltages across C9 and C11 is 4400V, as predicted by the above described procedure (see Fig. 5).

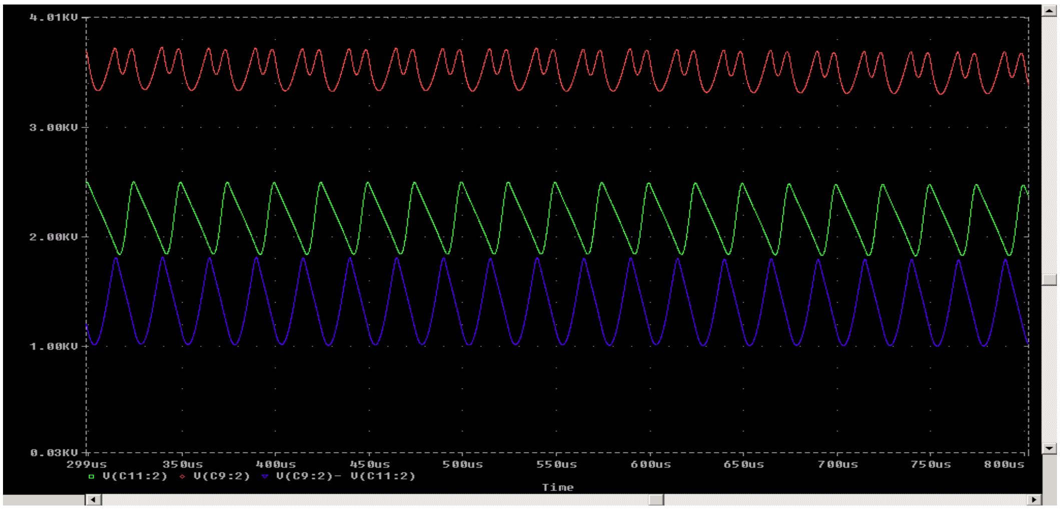


Figure 5: Pspice® simulation results

Measurements were performed on a commercially available magnetron power supply, having parameters very close to the ones calculated and simulated. Fig. 6 show the results. The inverter was based on IRG7PH42UD1, 1200V trench IGBT by International Rectifier Crop. Good agreement is found on both DC output voltage, primary switch peak voltage and peak current.

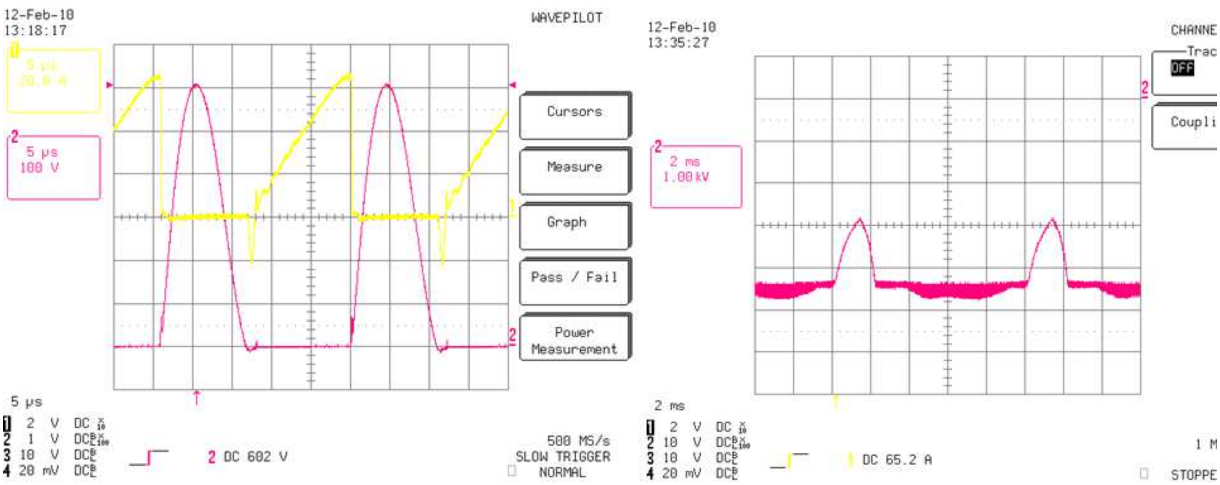


Figure 6 : experimental results

Conclusions

A simplified methodology for designing single ended resonant converter for microwave ovens has been introduced. Despite the analytical treatment is not completely precise, such methodology gives some guidelines to size the HV transformer, resonating components and gives a reasonable approximation of the stress level across the primary switch and across the voltage multiplier components.

References:

a) Analysis of MicroWave Ovens for 115V and 230V line; C.Bocchiola; internal IR Report

b) Whirlpool AWM839 user manual

c) EP1806954A1, Matshushita Electric Industrial Co.

d) The complete microwave oven service handbook; J.Carlton Gallawa; 1989-2009.