# The Relationship among Damped Oscillation, f-z characteristics and Conducted EMI of an Induction Cooking

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**Abstract**: This paper describes the relationship among damped oscillation, frequency-impedance characteristics (f-z characteristics) and conducted EMI occurring in induction cooking. The R-L-C equivalent circuit of induction pot is proposed. The relationship among ring, f-z characteristic and conducted EMI are verified by experiment. Finally, the reduction technique for damped oscillation is proposed using R-C series technique.
**Keyword:** Induction cooking, EMC and EMI

## 1. Introduction

Melting, welding, cooking and other applications of induction heating, all of them use the same concept by applying the high frequency current through the winding coil around the metal. The induction process between winding coil and metal produces the eddy current. The heat at the metal is generated by the eddy current. However, the induction process is also produce high frequency noise which directly affect to EMI problem.

It is well known that damped oscillation or ringing is directly effect to differential mode noise which dominant at frequency range less than 2 MHz [2]. The ringing current can equivalent by series and parallel resonance circuit which compose of resistor, capacitor and inductor [1]. These equivalent circuits are defined by f-z characteristics of induction pot of induction cooking. The transient phenomena of equivalent circuits are used to predict the ringing and conducted EMI. In this paper, the series R-C circuit is proposed to reducing the ringing and EMI problem of induction heating application.

## 2. Generation of Damped Oscillation

2.1 Series resonance circuit

Series resonance circuit shows in Fig. 1. The capacitor $C_2$ is charged to voltage $E_0$. When switch SW is turned on, transient phenomena occurs in the circuit. Derivations of mathematics in frequency domain of S parameters are as shown in eqns. (1))-(2)

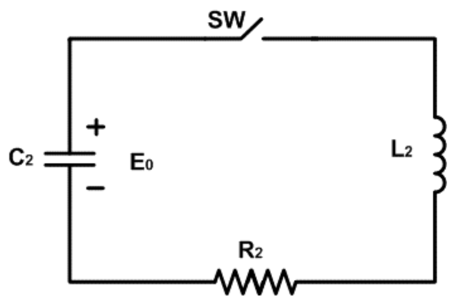



Fig. 1 The series resonance R-L-C circuit

$$S = -\frac{R_2}{2L_2} \pm \sqrt{\left(\frac{R_2}{2L_2}\right)^2 - \frac{1}{L_2C_2}} \qquad (1)$$

or

$$S = -\alpha_2 \pm \sqrt{\alpha_2{}^2 - \omega_0^2} \qquad (2)$$

Where

$$\alpha_2 = \frac{R_2}{2L_2} \text{ and } \omega_0 = \frac{1}{\sqrt{L_2C_2}} \qquad (3)$$

The damped oscillation will be occurred if:

$$\alpha_2 \langle \omega_0 \qquad (4)$$

Therefore, the angular frequency of damped oscillation is shown in equation (5).

$$\omega_2 = \omega_{ringing} = \sqrt{\omega_0^2 - \alpha_2^2} \qquad (5)$$

Because In equation (5), $\alpha_2$ is very small therefore it can be neglected. The frequency of damped oscillation becomes:

$$\omega_2 = \frac{1}{\sqrt{L_2C_2}} \qquad (6)$$

The ringing current flowing through the circuit is shown in eqn. (7)

$$i_2 = -\frac{E_0}{\omega_2 L_2} e^{-\alpha_2 t} \sin(\omega_2 t) \qquad (7)$$

At the resonance point, the reactance $X_2$ can be defined.

$$X_2 = \omega_2 L_2 = \frac{1}{\omega_2 C} = \sqrt{\frac{L_2}{C_2}} \qquad (8)$$

Sharpness of resonance is defined as

$$S_2 = \frac{X_2}{R_2} \qquad (9)$$

If $S_2$, $f_2$ and $X_2$ parameters can be determined, damped oscillation waveform can be produced even if the values of $R_2$, $L_2$ and $C_2$ are quite complicate to find.

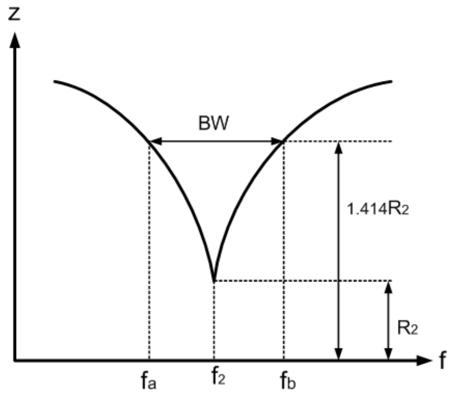



Fig.2 The f-z characteristic of series resonance R-L-C circuit

The value of $R_2$ and $f_2$ can be carried out from f-z characteristic of series resonance circuit shown in Fig. 2 and $S_2$ and $X_2$ can be calculated as shown in eqns. (10), (11) and (12), respectively.

$$BW = f_b - f_a \qquad (10)$$

$$S_2 = \frac{f_2}{BW} \qquad (11)$$

$$X_2 = R_2 S_2 \qquad (12)$$

From these three parameters of $S_2$, $f_2$ and $X_2$, the damped oscillation waveform can be plotted as shown in Fig. 3.

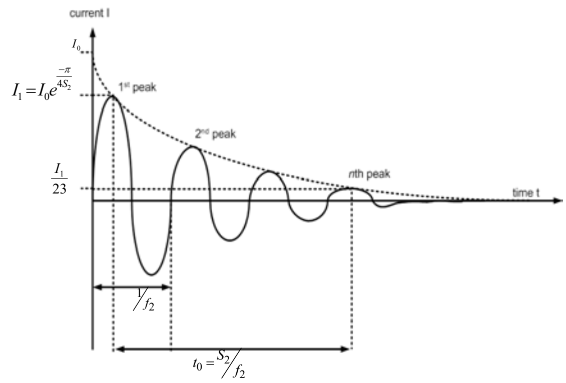



Fig. 3 The ringing current of series resonant R-L-C circuit

2.2 Parallel resonance circuit

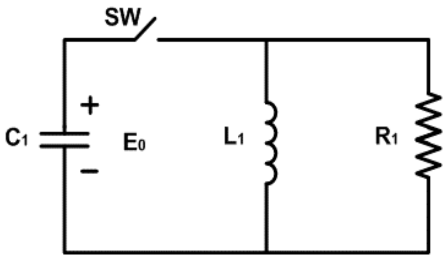



Fig. 4 The parallel resonance R-L-C circuit

In the same concept with series resonance circuit, the damped oscillation will be occurring if

$$\alpha_1 < \omega_0 \qquad (13)$$

Where

$$\alpha_1 = \frac{1}{2R_1 C_1} \qquad (14)$$

The angular frequency of damped oscillation also becomes

$$\omega_1 = \frac{1}{\sqrt{L_1 C_1}} \qquad (15)$$

In parallel resonance circuit, $S_1$ is defined as shown in equation (16).

$$S_1 = \frac{R_1}{X_1} \qquad (16)$$

The f-z characteristic of parallel resonance of R-L-C are plotted as shown in Fig. 5

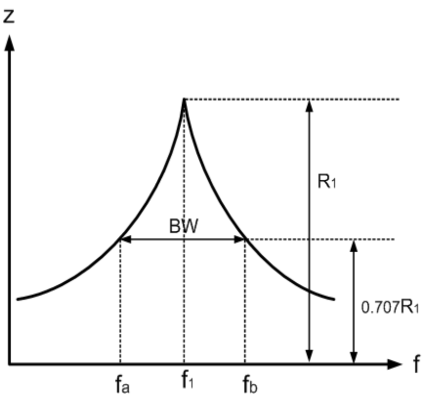
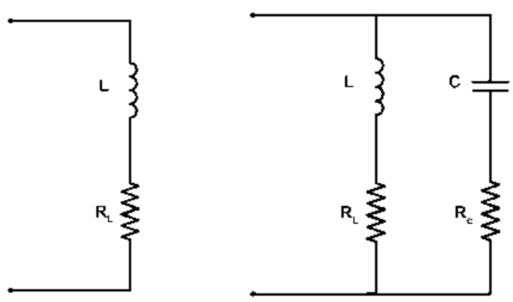


Fig. 5 The f-z characteristic of parallel resonance R-L-C circuit

2.3 The principle of R-C series technique applying to Induction pot

The equivalent circuit of induction pot is R seried with L that shows in Fig.6 (a). The proposed R-C series technique is paralleled with the induction pot as shown in Fig. 6 (b)



(a) (b)

Fig. 6 The equivalent circuit
(a) The equivalent circuit of induction pot
(b) The equivalent circuit of R-C series technique applying to Induction pot

The resonance frequency of equivalent circuit shown fig. 6 (b) can be calculated as

$$f_r = \frac{1}{2\pi}\sqrt{\frac{R_L^2 - L/C}{R_C^2 - L/C}} \tag{17}$$

From eqn. (17), the resonance can occur at all frequency if eqn. (19) is met.

$$R_L^2 = R_C^2 = \frac{L}{C} \tag{18}$$

$$R_L = R_C = \sqrt{\frac{L}{C}} \tag{19}$$

## 3. The relationship among f-z characteristic, damped oscillation and conducted EMI

3.1 Without R-C series technique

The relationship among f-z characteristic, damped oscillation and conducted EMI are verified by the experiment.

Fig. 7 shows the full-bridge inverter circuit of induction cooking that use in the experiment. Fig. 8 shows the f-z characteristic of inductor pot. The first parallel resonance appearing at frequency is equal to 3.144 MHz. It exactly equals to the ringing frequency in case of without R-C as shown in Fig. 9 (a).

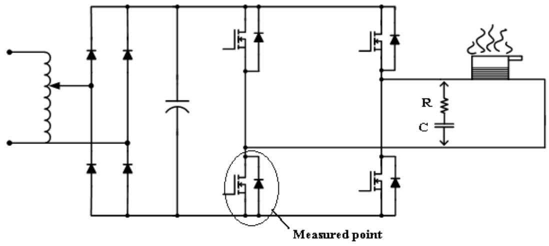


Fig. 7 Full-bridge inverter circuit of induction cooking

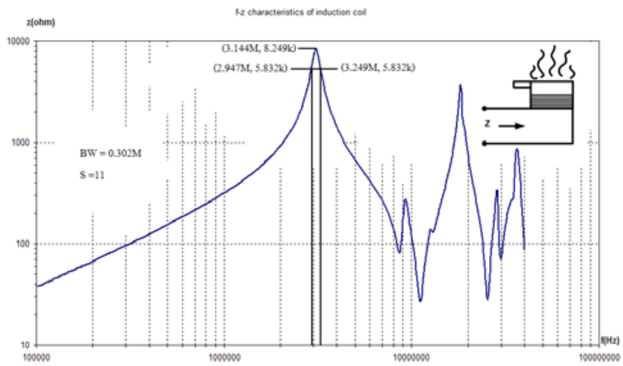


Fig. 8 The f-z characteristic of induction pot

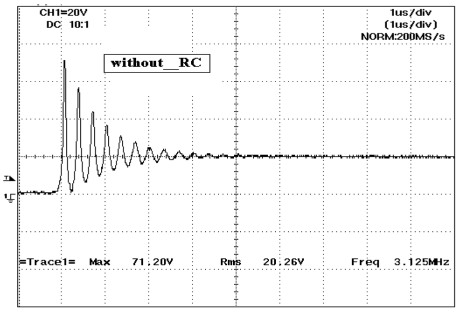
3.2 With R-C series technique

The R-C series technique is proposed to reduce the ringing of induction cooking. The experiment in case of insertion the R-C series technique is divided in three cases as shown in Table 1.

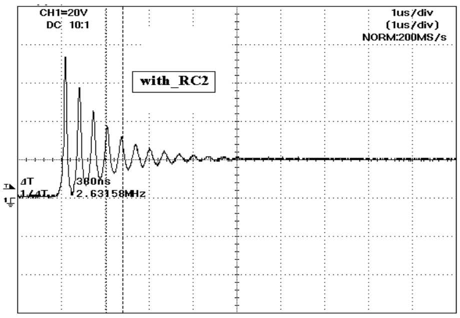
Table 1: The value of R-C series technique

| Case | R (Ω) | C (F) |
|---|---|---|
| With _RC1 | 1k | $100*10^{-12}$ |
| With _RC2 | 300 | $470*10^{-12}$ |
| With _RC3 | 7.5 | $600*10^{-9}$ |

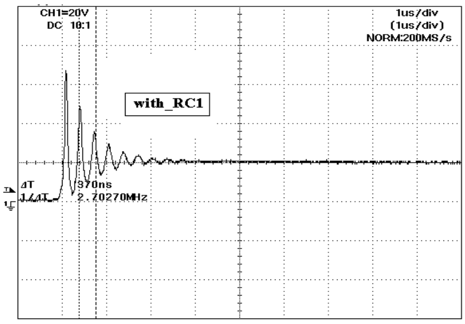
Figs. 9 (b) – (d) show the ringing frequency in case of insertion the R-C series technique parallel with the induction pot. The f-z characteristic comparison between without and with R-C series technique is shown in Fig. 10. The ringing frequencies of Fig. 9 (b) – (d) are also exactly similar with f-z characteristic of Fig. 10. The EMI comparison between without and with R-C series technique is shown in Fig. 11.



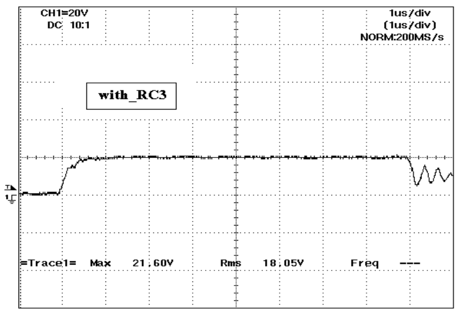

(a)




(b)




(c)




(d)

Fig. 9. The damped oscillation at measured point
(a) without R-C series technique
(b) $R = 1k\Omega$, $C = 100$ pF
(c) $R = 300\Omega$ , $C = 470$ pF
(d) $R = 7.5\ \Omega$, $C = 0.6\ \mu F$

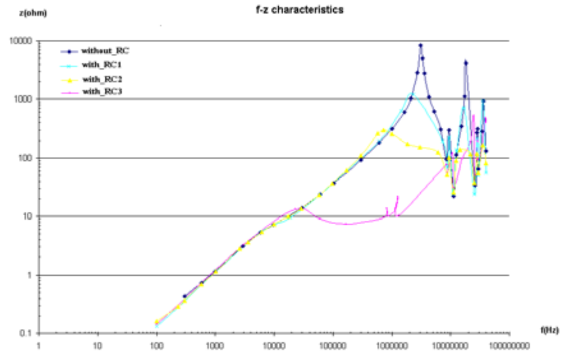



Fig. 10 The f-z characteristics comparison among 4 cases

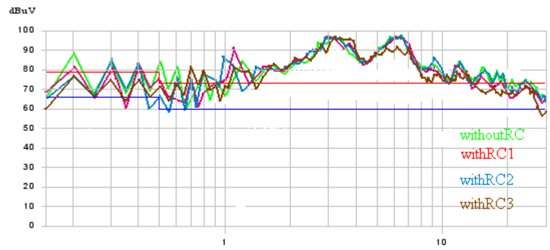



Fig. 11 The EMI comparison among 4 cases

The experimental results show the effect of ringing via conducted EMI. The proposed R-C series technique parallel to the induction pot can decrease the ringing and also the conducted EMI.

In case of without R-C series technique it can generate peak impedance as shown in Fig. 10 and also affect to EMI increasing as shown in Fig. 11. The concept of ringing reduction is to reduce the peak impedance of f-z characteristic, and then can reduce EMI. It can be confirmed by the relation between Fig. 10 and 11.

## 4. Conclusion

The f-z characteristic of induction pot can be used to predict the ringing frequency at main switch of induction cooking circuit. In the experimental results show the proportional relation between ringing and conducted EMI. The proposed R-C series technique parallel to induction pot also can decrease the ringing at main switch which affect to decrease the conducted EMI. The suitable parameter of proposed R-C series technique is verified by mathematic. However, this parameter is quite difficult to define in the practical.

## 5. References.

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[2] John C. Fluke, "Controlling conducted emissions by design", New York, Van Nostrand Reinhold, 1991