

# Analytical approach in finding the system parameters for the electromagnetic forming process

<sup>1</sup>Pratik Kumar, <sup>2</sup>Hitesh Choudhary, <sup>3</sup>Remadevi C, <sup>4</sup>Parul Ganvir  
<sup>1</sup>Mtech Student, <sup>2</sup>Scientific Officer, <sup>3</sup>Assistant Professor, <sup>4</sup>Mtech Student  
<sup>1</sup>Sardar Patel College of Engineering, Mumbai,  
<sup>2</sup>Accelerator and Pulse Power Division, Bhabha Atomic Research Center, Mumbai,  
<sup>3</sup>Sardar Patel College of Engineering, Mumbai,  
<sup>4</sup>Sardar Patel College of Engineering, Mumbai

**Abstract** - The study of a high-speed or an impulse forming process known as Electromagnetic Manufacturing, takes a large number of numerical models, depending on the arrangement of the job piece and working coil. The EMF process is too fast, takes about several micro hundreds to complete. Thus, it causes observation by experimental means very difficult. Consequently, designing of the coil is very crucial in the pulsed electromagnetic forming process, which further makes the computation of the system parameters even more paramount. This paper helps to formulate an analytical mathematical approach to calculate the parameters such as inductance and resistance theoretically, by making use of characteristics equation of series R-L-C circuit with R-L as the load and capacitor C as the source with initial voltage.

**keywords** - System parameters, electromagnetic forming process, underdamped current

## I. INTRODUCTION

Use of a pulsating magnetic field to apply magnetic pressure to job pieces preferably made up of highly conductive material without any proper mechanical contact or working medium. This high-speed forming technology is Impulse electromagnetic forming, commonly known as Electromagnetic forming [1]. In this technique, the job piece is inserted in between the coil with a pulsed sinusoidal high current, which in turn induces a current in the body of the job piece following the Faraday's Law. The current is opposite in direction due to Lenz's Law. By considering Maxwell Equations the currents flowing in their respective region produces a magnetic field in the direction opposite with another giving rise to magnetic pressure, which deforms the job piece. The deformation of the job piece is not necessarily uniform and controlled, in which case flux concentrator, widely known as field shapers are employed to focus the magnetic forces to the desired area. The process of electromagnetic forming mentioned is a state-of-the-art technique that shows advantages over the conventional quasi-static process like wrinkling, tearing, spring back, and any other effect on the job piece. It can very well be seen as one of the best high-rate forming techniques from various aspects such as high cleanness, cost-efficiency and productivity.

The above process is based on the idea that two current-carrying conductors produce opposite magnetic fields, which repel each other. Similarly, in the EMF process, one of the two current-carrying conductors is the working coil and the other is the job-piece (if the field shaper is not inserted in between the coil and job piece). Hence, for the EMF process to be performed, it requires to have a successful analogy of the two current-carrying conductors and also to have the location of both the conductors close to each other. By Lenz's law, the induced current in the job piece, called eddy currents. This current tends to counteract against the direction of the current flowing in the main coil. Consequently, the conductors are repelled from each other. The magnitude of the above-mentioned forming process mainly depends upon the geometric parameters of the construction and the electrical parameters [3].

## II. DESIGN METHODOLOGY AND CALCULATIONS

A simplified schematic circuit diagram of the process is given below in Figure 1.

The process involves elements such as:

- Capacitor banks, storing the electrical energy
- Fast switch, breaking and connecting the capacitor banks to the coil
- Magnetic coil, creating the magnetic field
- Job piece, to carry out the operation of compression and expansion
- Field shaper, to centralize the magnetic field to the desired area.

The process starts when the required number of capacitor banks discharges electrical energy into the job piece while the switch closes and a damped sinusoidal current starts flowing into the working coil [2]. The current flowing, produces an intense and transient time-varying magnetic field throughout the main working coil. Then, given Faraday's Law, when the working material is exposed to this magnetic field, eddy current is induced, in the reverse direction to current in the main coil. Therefore, two conductors with contrasting direction of currents lead them to repel each other, resulting in compression, if needed.

**Mathematical Design of the Process**

A capacitor with capacitance C provides an initial voltage,  $V_0$  which is given to the series RLC circuit and by using Kirchoff's voltage rule, we get;

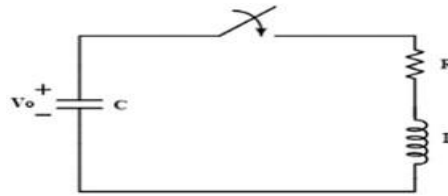


Figure 1 Circuit Diagram of Series R-L-C

The current supplied from the pulse  $\xi$  the B-field, the system inductance L, R and capacitance C and also the short circuit frequency  $f$ . The pulse generator is a simplified series RLC circuit with basic Equation (1) as given below:

$$V_0 = \left( \frac{1}{sC} + sL + R \right) i(t) \tag{1}$$

The maximum current required by the coil to produce B-field is given by solving the above equation in Laplace domain we get Equation (2) as:

$$I_{\max} = I(t) = \left( \frac{V_0}{L} \right) \frac{e^{-\zeta\omega_n t}}{\omega_d} \cdot \sin(\omega_d t) \tag{2}$$

Equation (3) shows the value of instantaneous voltage across the voltage.

$$V_L(t) = -V_0 \cdot \frac{e^{-\zeta\omega_n t}}{\sqrt{1-\zeta^2}} \cdot \sin(\omega_d t - \varphi) \tag{3}$$

Where,  $\varphi = \tan^{-1} \zeta$ .

By calculating the maximum current first, we will try and calculate the equation for the peak time  $T_{\text{Peak}}$

To find the maximum value we use,  $\frac{di(t)}{dt} = 0$ ;

$$\frac{di(t)}{dt} = \left( \frac{-\zeta\omega_n}{\omega_d} \right) e^{-\zeta\omega_n t} \cdot \sin(\omega_d t) + \omega_d \left( \frac{e^{-\zeta\omega_n t}}{\omega_d} \right) \cdot \cos(\omega_d t) = 0$$

Steady-state:

$$\sin(\omega_d t - \varphi) = 0$$

Where  $\zeta$ ,  $\omega_n$ ,  $\omega_d$  are damped ratio, natural frequency and damped frequency respectively

$$\omega_d t - \varphi = n\pi \tag{4}$$

By substituting  $T_{\text{Peak}}$  in place of t, we will get the peak time,

$$T_{\text{Peak}} = T_{Pn} = \frac{n\pi + \varphi}{\omega_d} \tag{5}$$

**Calculation for the System Parameters**

The information we acquired through various experimentations are different peak current with their related peak time, represented as  $I_{Pn}$  and  $T_{Pn}$ , respectively, where n is to denote the number of the peak which is under observation. From Equation (5) we can consider the following peaks of the current waveform at different periods  $T_{P1}$ ;  $T_{P2}$ ;  $T_{P3}$ ...

Considering equation for  $T_{Pn}$ ,

$$\begin{aligned} T_{P1} \text{ at } n=0, \quad t_{p1} &= \frac{\varphi}{\omega_d} \\ T_{P2} \text{ at } n=1, \quad t_{p1} &= \frac{\pi + \varphi}{\omega_d} \\ T_{P3} \text{ at } n=2, \quad t_{p1} &= \frac{2\pi + \varphi}{\omega_d} \end{aligned}$$

Now using these various peak periods to calculate their respective current peaks, such as

$$I_{P1} = \frac{V_0}{\omega_d L} \cdot \exp \left[ -\zeta\omega_n \left( \frac{\varphi}{\omega_n \sqrt{1-\zeta^2}} \right) \right] \sin(\varphi) \tag{6}$$

$$I_{p3} = \frac{V_3}{\omega_d L} \cdot \exp \left[ -\zeta \omega_n \left( \frac{\pi + \varphi}{\omega_n \sqrt{1 - \zeta^2}} \right) \right] \sin \left( \frac{2\pi + \varphi}{\omega_d} \right) \cdot \omega_d \tag{7}$$

$$\log \frac{I_{p1}}{I_{p3}} = \frac{\xi \pi}{\sqrt{1 - \xi^2}} \tag{8}$$

Since the peak currents  $I_{p1}$  and  $I_{p3}$  are known we can directly substitute these values in equation (10) respectively, it will help in finding the damping value  $\xi$ . Next, to calculate the damped frequency we will use the value of the period T, from the first complete cycle of oscillation of the damped sinusoidal current  $i(t)$  in Equation (2).

$$\omega_d = \frac{2\pi}{T} \quad , \quad \omega_n = \frac{\omega_d}{\sqrt{1 - \xi^2}} \tag{9}$$

$$\omega_n = \frac{1}{\sqrt{LC}} \tag{10}$$

$$R = 2\xi \sqrt{\frac{C}{L}} \tag{11}$$

The values of  $\omega_d$  we found is substituted in equation (9) from where we get the natural frequency  $\omega_n$  is then used to obtain total inductance of series RLC circuit L from equation (10), since capacitance C is already known. The inductance L we obtain is further used similarly to find the total resistance of the circuit R, from equation (11).

### III. EXPERIMENTAL RESULTS

Figure 2 below shows the waveform from the Digital Storage Oscillator (DSO). The x-axis of the waveform is represented by time (seconds) and similarly the y-axis by Voltage (Volt). The distribution of the sample is 500mV/unit along the y-axis and 150µsec/unit along the x-axis. The data is extracted from the DSO with the help of a Rogowski coil and passed through a current transducer with sensitivity: 1V=100kA.

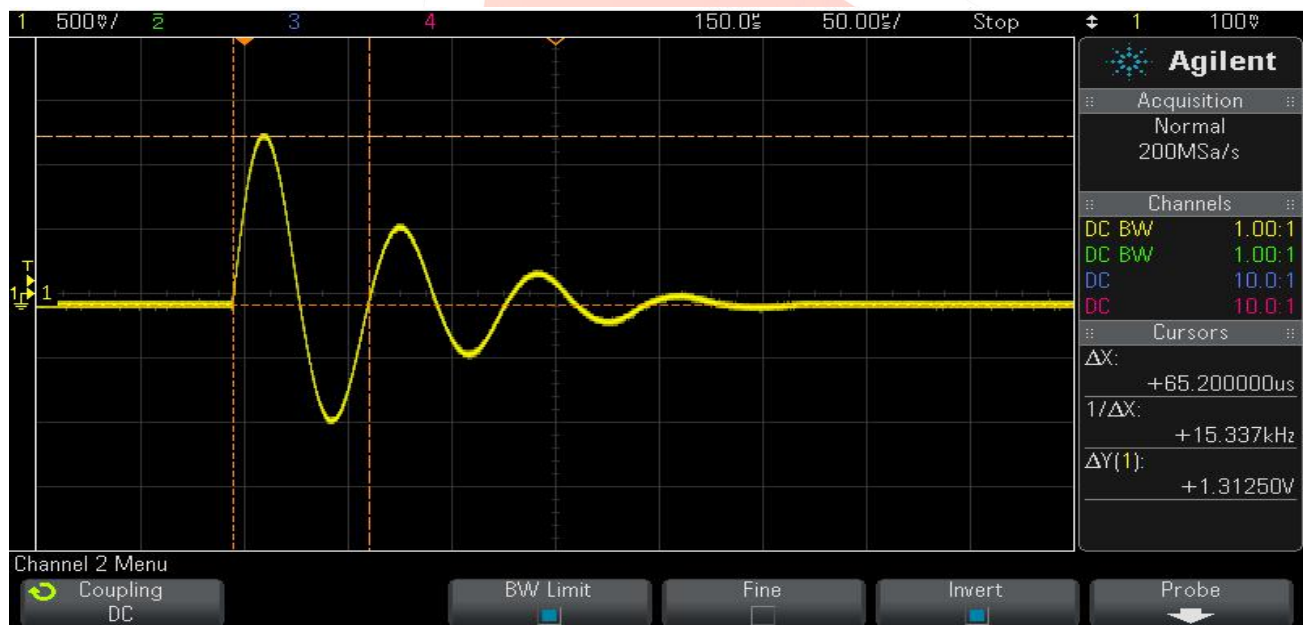


Figure 2 Experimental waveform from the DSO

The above waveform is for the experiment performed on a Copper-Maraging Steel coil. The capacitors were charged up to 6.9kV. The period for a cycle to complete is 65.2µsec, as seen in Figure 2.

The peak currents as already mentioned are known i.e. the values of  $I_{p1}$  and  $I_{p3}$  are 134.375kA and 60.625kA respectively. For the theoretical calculations, we can directly substitute the values of peak currents in the Equation (8). The result which we obtain from the mentioned substitution is the damping ratio  $\xi$  as 0.2456. Similarly, we can also compute the values of damped frequency,  $\omega_d$  as 96367.8 rad/sec and natural frequency,  $\omega_n$  as 99412.76 rad/sec, from their respective Equation (9). Now, Equation (10) and Equation (11) can help us to calculate a theoretical value of the system's inductance and resistance, i.e. L and R, respectively.

Table 1 Comparison between Experimented and Calculated values of the System Parameters

System Parameters	Inductance, L (nH)	Resistance, R(mΩ)
Calculated Value	451.7	22.06
Experimented Value	473.7	10.86

Table 1 makes a comparison between theoretical and practical system parameters. We can use peak periods such as  $T_{P1}$ ;  $T_{P2}$ ;  $T_{P3}$  and so on, to track back the underdamped sinusoidal current waveform analytically as shown in Figure 3.

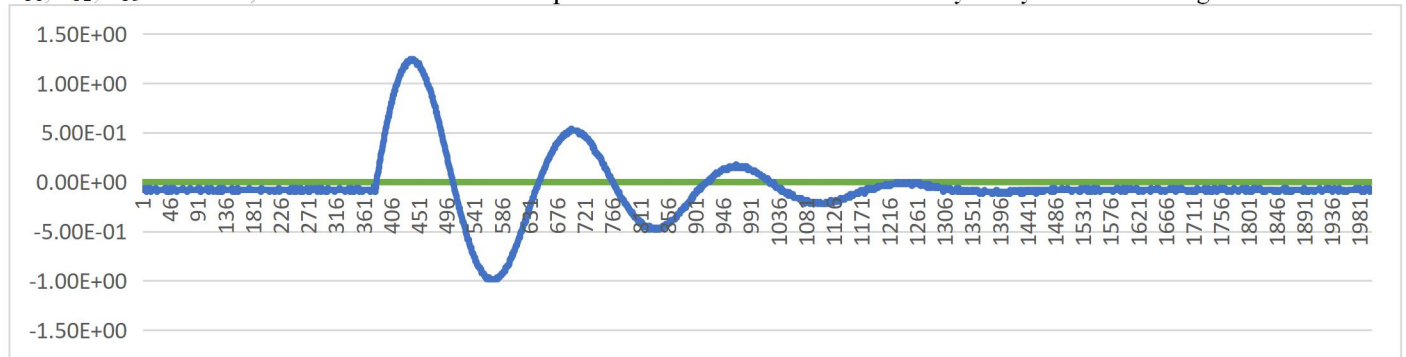


Figure 3 Waveform of computed system parameters

**IV. Conclusion**

From this paper, we can conclude that the mathematical equations derived can be made useful in tracking back the underdamped sinusoidal waveform, which in turn can validate the analytical approach. Thus, we can use them to compute the system parameters of inductance and resistance.

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