REDUCTION OF THE INRUSH CURRENT IN AN ELECTRICAL TRANSFORMER USING THE VOLTAGE DOWN-CHIRP TECHNIQUE

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Abstract

This study aims to examine the reduction of the inrush current on a single-phase transformer when there is no power transmission by using the voltage down-chirp technique. The transformer is initially pressured with a frequency higher than the frequency range. Then, such frequencies are downgraded to equal the frequency range of the transformer in a short span of time, resulting in the reduced size of the magnetic flux on the magnetic axis and line of the transformer. The design of the process and simulation rely on MATLAB Simulink software. The results of the stimulation of the 1200 VA transformer showed that the inrush current was reduced when the default frequency of the voltage is equal to 90Hz.

Keywords: Inrush current, transformer, down-chirp techniques

Introduction

The inrush current in a transformer has a higher rated electrical current, and the voltage is asymmetric (Turner and Smith, 2010), resulting from the instantaneous electricity distribution to the transformer which causes a momentary electric current with increased amplitude values up to 10 times the current primary coil of the transformer with no power transmission (Taylor *et al.*, 2012). An occurrence of the inrush current of a transformer in transmission lines, distribution systems, or coordinated low voltage transformer is an important concern for a protective device because the protective equipment may view the excessive current as a short circuit current and may cause the circuit

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breaker of the transformer to operate (Chiesa and Hoidalen, 2010). Frequent occurrences of the inrush current may directly damage the transformer coils as well. Although the inrush current has a negative impact on the power transformer, it can be used to estimate the transformer's saturation characteristics (Abdulsalam *et al.*, 2006). There are several methods that can be used to reduce the inrush current in a power transformer, such as using prefluxing (Taylor *et al.*, 2012), using the virtual air gap technique (Molcrette *et al.*, 1998), and the line-interactive uninterruptible power supply system (Chen and Chen, 2010), but most of those methods are also simulation systems and difficult to put into practice with real problems.

Reviewing such existing issues, the researchers conducted this study to provide ways to reduce the amount of the inrush current occurring in the transformer by employing the down-chirp method on the voltage of the supply to reduce the amount of excess flow. The results of the study provide guidelines for further development of inrush current reduction.

Notations

$v(t)$	:	Transformer-supplied voltage
$V_{\max}$	:	Maximum voltage of supply
$\phi_{\max}$	:	Maximum magnetic flux
N_P	:	Turns of wiring
ω	:	Angular frequency
f	:	Ordinary frequency

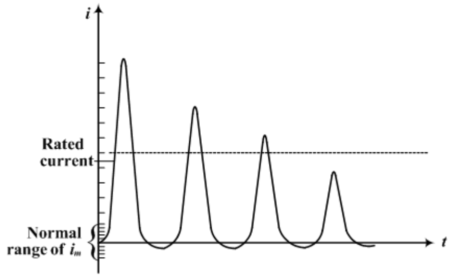


Figure 1. The inrush current in the transformer

Inrush Current in a Transformer

The connection between the transformer and the supply results in a momentary overload current or inrush current in the primary circuit that is higher than the rated current because of the change of the magnetic flux on the transformer's cores. The current quantity depends on the form of the coil, the transformer size, the structure of the axis, the residual magnetic flux on the transformer's cores, and the phase sequence of the supply (Chapman, 2004). The characteristic pattern of the inrush current of the transformer is presented in Figure 1.

The change of the magnetic flux on a transformer according to the phase of the supply affecting the amount of the inrush current can be explained in Figure 2, which shows the direction of the magnetic flux occurring on the axis of the transformer when the transformer has the maximum voltage. It was determined from the following equations:

$$v(t) = V_m \sin(\omega t + \theta) \text{ V} \qquad (1)$$

The maximum flux height reached on the first half-cycle of the applied voltage depends on the phase of the voltage at the time the voltage is applied. If the initial voltage is

$$v(t) = V_M \sin(\omega t + 90°) = V_M \cos \omega t \text{ V} \qquad (2)$$

and if the initial flux in the core is zero, then the maximum flux during the first half-cycle

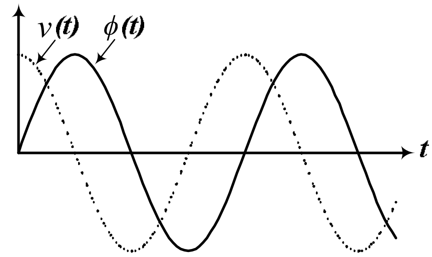


Figure 2.The phase voltage and magnetic flux of the transformer

will just equal the maximum flux at a steady state, that is

$$\phi_{\max} = \frac{V_{\max}}{\omega N_p} \tag{3}$$

This flux level is just the steady-state flux, so it causes no special problem. However, if the applied voltage happens to be

$$v(t) = V_M \sin \omega t \quad \text{V} \tag{4}$$

the maximum flux during the first half-cycle is given by

$$\phi(t) = \frac{1}{N_P}\int_0^{\pi/\omega} V_M \sin \omega t \, dt$$

Integrating gives

$$\phi_{\max} = \frac{2V_{\max}}{\omega N_P} \tag{5}$$

This maximum flux is twice as high as the normal steady-state flux in the core and results in both an enormous magnetization current that looks like a short circuit and a very large current flow that are shown in Figure 1.

Equations (1) to (5) represent the factors that affect the magnetic flux values occurring on the transformer while receiving voltage. The phase position of the supply is significant and directly affects the quantity of the

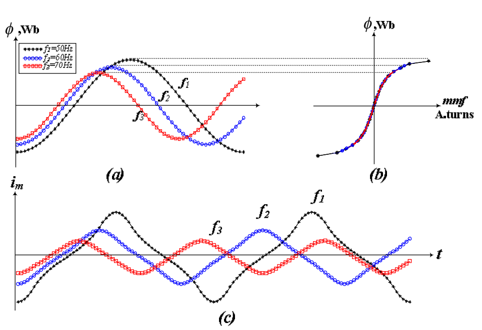


Figure 3.(*a*) Magnetic flux on the transformer's cores; (*b*) magnetization curve; (*c*) magnetization current

magnetic flux. The changes of the flux values result in the relationship between the magnetic flux and the magnetomotive force by considering the transformer's magnetization curve. If the magnetization curve of the transformer is increased, the inrush current will increase correspondingly. Therefore, if the quantity of the magnetic flux is controlled and reduced, the amount of the inrush current on the transformer can be controlled and reduced as well.

The Reduction of the Inrush Current in Electrical Transformer

An effective way to reduce or limit the inrush current in an electrical transformer while it is running with power is to control the quantity of the magnetic flux on the transformer's axis so that the value decreases. Equation 4 presents a variable that defines the quantity of the magnetic flux, such as the maximum voltage of the supply ($V_{\max}$), the number of the cycles of the transformer's coils (N_P), and the angular frequencies ω. This research, therefore, focuses on the way to reduce or limit the inrush current from the supply frequency $\omega = 2\pi f$ to change the performance of the angular frequency and the values of the magnetic flux.

Changing the frequency of the supply to a value higher than the frequency range while there is electrical power in the transformer causes the magnetic flux values to decrease due to the increase of the angular frequency ω. As a result, the magnetization curve of the transformer gets smaller. The values of the inrush current are a direct variable in the change of the magnetization curve. The characteristics of the changes of the magnetization curve and the magnetization current according to the frequency of the supply are presented in Figure 3.

Figure 3(a) demonstrates the change of the magnetic flux in the transformer when the transformer's coils receive the voltage with different frequency values. It can be noted that if the frequency of the supply has a higher value, the quantity of the magnetic flux is reduced, resulting in the changes of the magnetization curve of the transformer. In addition, the saturation of the transformer's core occurs quickly, as shown in Figure 3(b). The performance of the magnetization current of a normal frequency is different from the sine signal. However, when the transformer gets a higher frequency value, the magnetization current changes its shape and becomes similar to a sine signal, as shown in Figure 3(c). From this process, it can be explained that to increase the frequency of the voltage until it is higher than the frequency range of a transformer is a method that can be used to reduce the amount of the inrush current in the transformer.

Down-Chirp Technique

A chirp technique (Weisstein, 2015) is a signal in which the frequency increases (up-chirp) or decreases (down-chirp) with time. It is commonly used in sonar and radar, but has other applications, such as in spread-spectrum communications, surface acoustic wave devices, optics, ultrashort laser pulses, and increasing or decreasing the total pulse dispersion as the signal propagates.

The down-chirp of the supply voltage to reduce the inrush current in a transformer refers to the change in the frequency of the voltage supplied to the transformer from a high frequency to a lower frequency range. That is, the transformer starts working with the high-frequency value voltage for a while before turning back to operate with a lower frequency range. The pattern of the voltage supply with the adaptive down-chirp model is shown in Figure 4, which presents the voltage supplied to the transformer. The frequency of the signal is changed in the form of a linear equation as shown in the equation

$$f(t) = f_0 + \left[\frac{f_1 - f_0}{f_1}\right]t \qquad (6)$$

When the default frequency is f_0, f_1 is the last frequency. It was observed that the frequency of the voltage supplied to the transformer had a high value at the beginning, resulting in the saturation of the magnetic flux and reduction of the inrush current in the transformer.

Operational Testing

In testing the inrush current, this research study simulated the operation using MATLAB software. The coordinated information and important characteristics of the transformer used in the test are presented in Table 1; the performance of the inrush current in the 1200 VA 50 Hz transformer can be tested and simulated as shown in Figure 5, which shows the comparison of the simulation results obtained from the MATLAB Simulink software with the inrush current values which were actually measured with oscilloscopes. It was found that the values of the inrush current were approximately 10 times greater than the

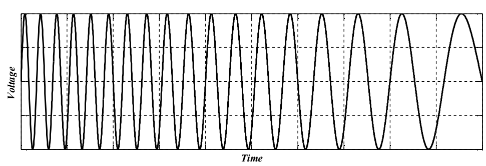
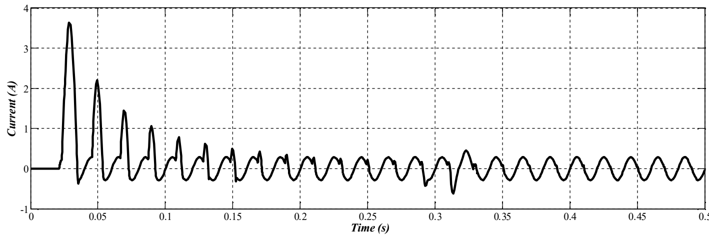


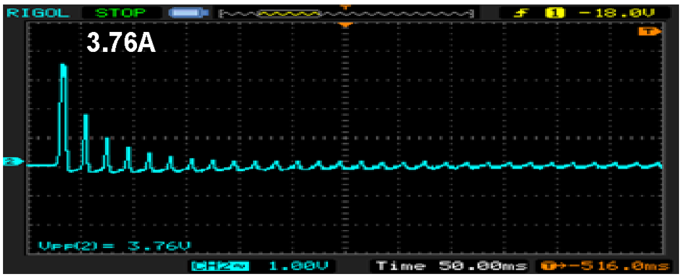
Figure 4.The voltage resulting from the adjustable frequency value with the down-chirp method

Table 1. Parameters of the 1200 VA 50Hz transformer

Parameter	Voltage (V)	Normal Current (A)	R (ohm)	L(H)
LV winding	115	0.35	8.27	0.148
HV winding	230	0.17	14.9	0.41



(a)



(b)

Figure 5. Inrush current: (a) results of the MATLAB simulation (b) results from the actual measurement

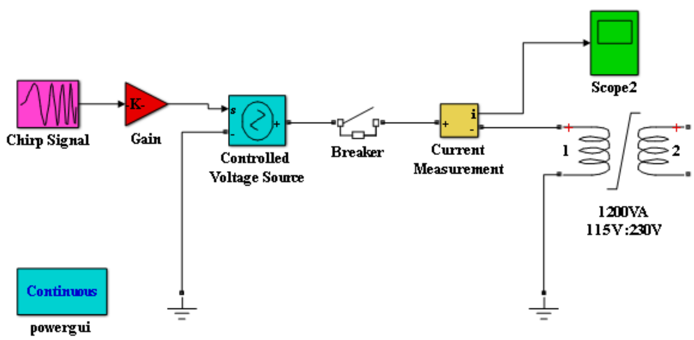


Figure 6. Circuit simulation of reducing the inrush current by the down-chirp supply voltage

normal currents in the transformer. Afterwards, the circuit was designed to reduce the values of the inrush current by the down-chirp of the supply voltage. The simulation of the circuit is shown in Figure 6.

Results

In the simulation of the initial configuration, the default frequency and the transformer's value of the frequency range of the chirp signal are controlled by comparing results from the default frequency value of 4 samples: 60 Hz,

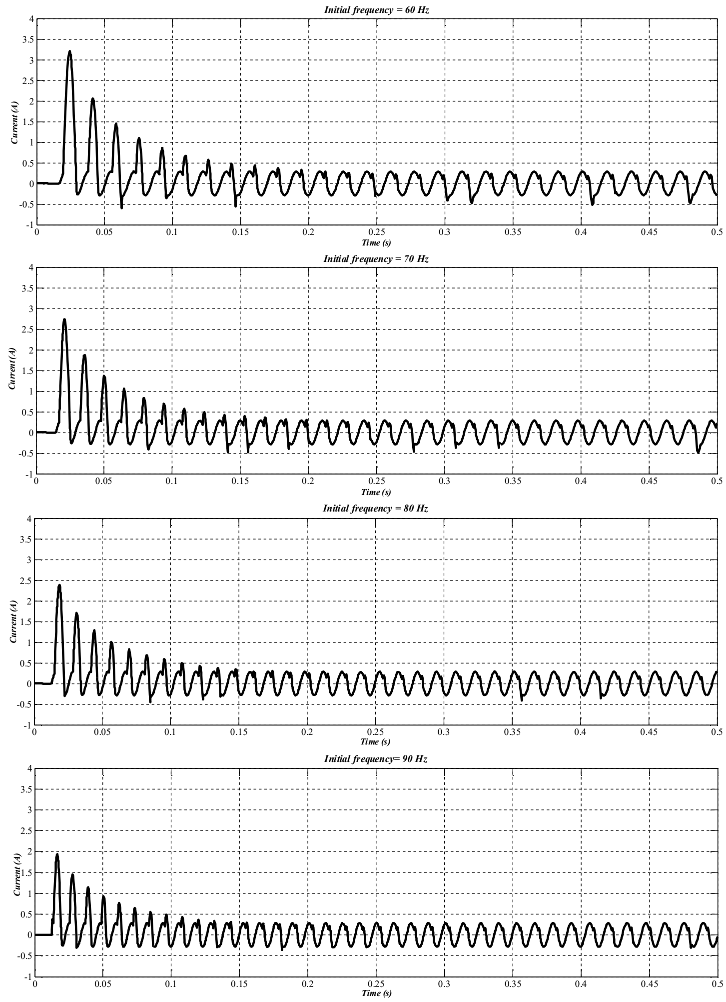


Figure 7. The result of inrush current reduction in the power transformer using the voltage down-chirp technique

70 Hz, 80 Hz, and 90 Hz, respectively. The results of the experiment determine the performance of the inrush current in the transformer as presented in Figure 7; it shows that the supply's default frequency of 60 Hz, 70 Hz, 80 Hz, and 90 Hz can reduce the excess flow down to 3.25A, 2.7A, 2.4A, and 1.85A, respectively. This research study suggests that the amount of excess currents can be reduced by up to 50% of the actual inrush currents which were measured.

Conclusions

The down-chirp of the frequency of the supply is a method that can be effectively used to reduce the inrush current of the transformer. The quantity of the inrush current depends on the default frequency of the voltage supplied to the transformer. Practically, in using such a technique, the operation of the equipment has the capability to control the frequency of the voltage and the ability to modify the default frequency value of the transformer.

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