REDUCTION OF MAGNETIZING INRUSH CURRENT IN THE TRANSFORMERS

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ABSTRACT:

This paper deals with the magnetizing Inrush Current Phenomenon, its causes and remedies. This investigation considers the mathematical analysis of inrush current to find the best instant of switching in the transformer. An electronic triggering circuit, which can be adjusted to switch on at a selected instant of switching, depending on the transformer parameters, has been designed. The circuit operation has been tested in a real transformer. Oscillograms of *magnetizing current* waveforms have been discussed with and without introducing the proposed switching circuit. It has been inferred that the proposed triggering circuit has reduced the value of the inrush current appreciably.

1. Introduction

When switching ON the transformer at no-load, ammeter, often, registers an initial current which is many folds greater than the magnitude of the normal no-load current and sometimes even much greater than the normal full-load current of the transformer. It is noticed that this current rush rapidly dies down. In this case, it may seem at the first glance that there is a fault in the transformer. Upon considering the problem fully, however, and bearing in mind the characteristics of iron cored apparatus, the true explanation of the transient current rush will become clear [1].

Referring to the characteristic shape of the B/H curve of the transformer core steel, Figure 1, it is noticed that at twice the normal flux density, the no-load current is increased out of all proportions as compared with the current under steady state conditions [2]. The total current may be considered to consist of the normal no-load current and drooping characteristic transient current

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superimposed upon it. Due to the initial high saturation in the core, the current waves may be extremely peaked and contain prominent third harmonics, as illustrated in Figure 2, [1].

The initial value of the current taken at no-load by the transformer at the instant of switching ON, is principally determined by the point of the voltage wave at which switching occurs, but it does also partly depend upon the magnitude and polarity of the residual magnetism which left in the core after previously switching OFF [1].

Many attempts have been made in the past to analyse and simulate the inrush current phenomenon, [3,4,5,6].

This inrush current causes mechanical forces between coils at the instant of switching ON. While this certainly dies down more or less rapidly, the conductors may become compressed in places, while in other places the normal mechanical pressure due to the winding process may be released, so that the mechanical rigidity of the coils as a whole becomes entirely altered. That is in some parts adjacent conductors may be slack, while in others may be compressed, tightly, and with repeated switching operations there may be a serious risk of failure of the insulation between turns of the windings. Cases have been known when the a transformers switched ON under particularly adverse conditions. This introduces the possibility of damage the connections between coils and connections from coils to terminals, resulting in open circuits in the windings concerned. Among the minor disadvantages, also, are the tripping of main switches, blowing of fuses, and operation of relays [1].

This investigation considers the mathematical analysis of the transformer equivalent circuit to find the best instant of switching ON the transformer which results in a minimum inrush current. It includes the design of a triggering circuit to switch ON at the best instant of switching. Oscillograms of magnetizing current waveforms have been discussed with and without introducing the proposed switching circuit. It has been inferred that the proposed switching circuit has reduced the value of the inrush current appreciably.

2. Mathematical Analysis

Assuming that the applied voltage on the transformer varies sinusoidally, regardless of the operating conditions. Figure 3 shows the equivalent circuit of the transformer in case of no-load. The e.m.f. equation at the moment when the transformer is switched ON can be written as:

$$V = V_m \sin(\omega t + \alpha) = i_o r_1 + L_1 \frac{di_o}{dt}$$

where;

V is the applied voltage, V_m is the maximum applied voltage; α is the phase angle which determines the value of V at the moment of switching, i_o is the magnetizing current, r_1 is the primary winding resistance and L_1 is the primary leakage inductance.

Since the relation $\phi_1 = f(i_0)$ is of a complex nature determined by the transformer magnetization curve, the solution of the above equation is only possible under the simplifying assumption that the flux ϕ_1 is a linear function of the current i_o, (i.e. $N_1\phi_1 = L_1 i_1$) where, L_1 is a constant inductance corresponding to the flux linked with the primary winding. Hence,

$$V_m \sin(\omega t + \alpha) = \frac{N_1\phi_1}{L_1} r_1 + N_1 \frac{d\phi_1}{dt}$$

$$\therefore \frac{d\phi_1}{dt} + \frac{r_1}{L_1}\phi_1 = \frac{V_m}{N_1} \sin(\omega t + \alpha) \quad \text{.....................} \quad (1)$$

The solution of the above differential equation (1) is;

$$\phi_1 = \phi_m \left[\sin(\omega t + \alpha + \theta) - \sin(\alpha + \theta) e^{-\frac{r_1}{L_1}t} \right] \pm \phi_r e^{-\frac{r_1}{L_1}t} \quad \text{.....................} \quad (2)$$

where;

$$\phi_m = \frac{V_m L_1}{N_1 \sqrt{r_1^2 + \omega^2 L_1^2}}$$

Since, usually, $r_1 << \omega L_1 \qquad \therefore r_1 \cong 0$

$$\because \tan(\theta) = \frac{-\omega L_1}{r_1} \therefore \theta = -\frac{\pi}{2}$$

Substituting in equation (2) will result in the following equation :

$$\phi_1 = \phi_m \left[\cos(\omega t + \alpha) - \cos(\alpha) e^{\frac{-r_1}{L_1}t} \right] \pm \phi_r e^{\frac{-r_1}{L_1}t} \quad \text{.....................} \quad (3)$$

It is evident from the above equation that the best conditions for switching ON, are when, $\alpha = \frac{\pi}{2}$ and the residual magnetism is zero, i.e. $\phi_r = 0$. Equation 3 will then be as follows; $\phi_1 = \phi_m \sin(\omega t)$ which is corresponding to the steady state operation of the transformer.

On the other hand, the latest favorable conditions for switching-in are when $\alpha = 0$ and ϕ_r is positive as shown in Figure 4. As $r_1 << \omega L_1, \frac{r}{\omega L}\pi \cong 1$ hence the value of $\phi_1 = \phi_m + \phi_m + \phi_r \cong 2.25\phi_m$ which requires very high current with $\frac{i_{om}}{i_o}$ of up to 120.

The current usually takes 6 to 8 seconds to die down, but it takes more than 20 seconds in the case of the powerful high voltage transformers.

3- Triggering Circuit Design

Based on the above calculations, which that the magnitude of the inrush current is determined by the instant of switching, a triggering circuit was proposed to switch on at the best instant of switching. The design of this electronic circuit made control of the instant of triggering, which depends on the previous opening angle, possible. Figure 5, shows the block diagram of the proposed circuit.

This circuit controls the firing angle α of a triac placed in the neutral line of transformer primary side. The electronic triggering circuit consists of an A.C. source of 6V taken from the main supply through a small transformer, an inverting zero crossing detector which convert the sinusoidal wave to a rectangular one at zero positions, a ramp generator to produce a triangular wave matching the square one and a comparator to detect the intersections between the triangular wave and a d.c. reference controlling voltage varied through a potentiometer. The comparator output signal is fed to a differentiator to produce a variable pulse. This pulse is driven to the gate of a thyristor through an optoisolator. The input of this thyristor is supplied by a d.c.voltage to give a step wave produced as soon as the signal reached its gate. This signal is used then to switch on the transformer by applying it to the gate of the triac. So a controllable gating pulse at any selected instant of switching can be gained by varying the reference controlling voltage. The circuit performance is satisfactory.

4- Results and Discussion

The triggering circuit is used to switch-ON a 1kVA transformer which has a ratio of 1:1. An assumption of that the residual magnetism is zero is made. In this situation the best instant of switching, as found in section 2, is when $\alpha=\pi/2$ and the worse one is when $\alpha=0$. The potentiometer of the triggering circuit is adjusted to vary the controlling voltage to switch ON the transformer at a fixed angle of $\alpha=\pi/2$. The magnetizing current is then monitored, for both cases of with and without introducing the switching circuit at different instants of switching, through an oscilloscope which pitcks the current signal across a 2Ω resistor placed in the neutral path of the transformer. The oscillograms of the magnetizing current is recorded using a camera. A comparison between different oscillograms at different switching instants has showed that, introducing the circuit leads to reduced magnetizing inrush current appreciably. This indicates that the switching circuit is working satisfactorily to trigger at $\alpha=\pi/2$. The assumption that no, or a small, residual magnetism left in the core, after a previous opening, is satisfied. This can be owed to the small rating of transformer, while in the large ones, the residual magnetism has be taken into consideration.

Figures 6,7,8,9,10,11,12 and 13 show the magnetizing current at instants of $\alpha=0$, $0<\alpha<\pi/2$, $\alpha=\pi/2$, $\pi/2<\alpha<\pi$, $\alpha=\pi$, $\pi<\alpha<3\pi/2$, $\alpha=3\pi/2$ and $3\pi/2<\alpha<2\pi$ for both cases of with and without introducing the switching circuit. It is found that the best instant to switch in a transformer is at $\alpha=\pi/2$, $\alpha=3\pi/2$ and the worse one is at $\alpha=0$. From these oscillograms, we can find that the electronic switching circuit is a useful tool for limiting the magnitude of the magnetizing inrush current to a low value, if not eliminating it.

5- Conclusion

The switching inrush current of a transformer at no-load can be reduced appreciably by switching ON when the supply voltage assumes its positive peak value. However, this reduction depends on the magnitude and polarity of the residual magnetism in the transformer core. As it is difficult to determine such a residual, it has been assumed that there is no residual magnetism in the core, which is negligible in this under-test small transformer.

In this work, an electronic circuit is designed to switch ON a transformer at the peak positive value of the supply voltage, i.e. at an instant $\alpha=\pi/2$, although the switching angle of the circuit can be varied to accommodate any changes in the transformer core condition, such as the residual magnetism if it is defined. Oscillograms of the magnetizing current waveform at different switching angles have discussed for the two cases of with and without introducing the proposed triggering circuit. It has been inferred that the proposed circuit reduces the value of inrush current appreciably. The obtained results satisfy the purpose for which the circuit was designed. Thus, the discrimination between the inrush starting current and the short circuit current will make the protection devices act correctly. This will help also the transformer to have a longer life span, by avoiding the coils stresses that results from the transient inrush current.

It is recommended to extent the above proposed solution to the case of multi-phase transformers, after considering the shifts between phases and residual magnetism in case of transformers with high ratings.

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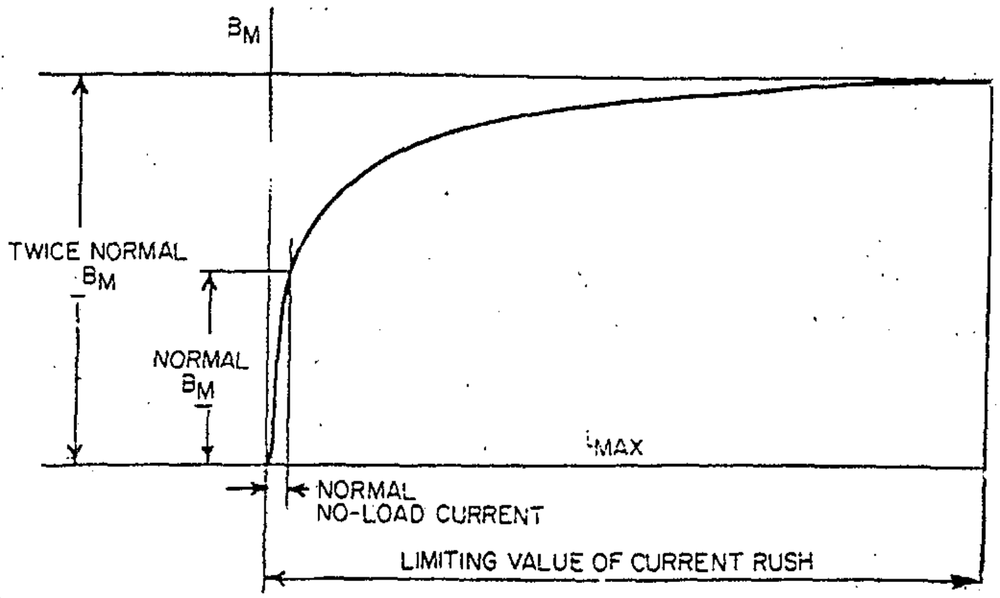


Figure 1 Typical B/H Curve Showing relationship between maximum flux density and no-load current.

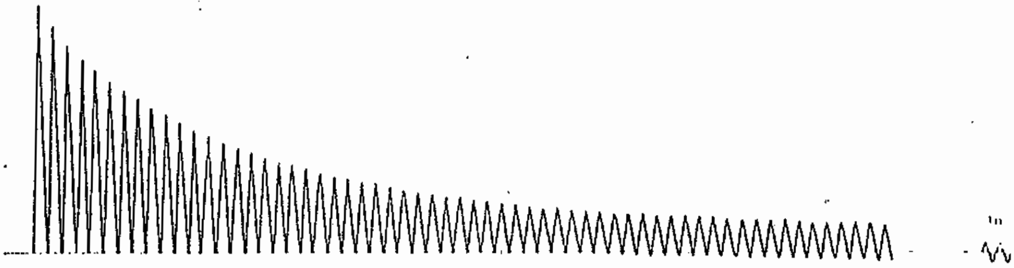


Figure 2 Typical transient inrush current when switching in a transformer at the instant v=0 [1]

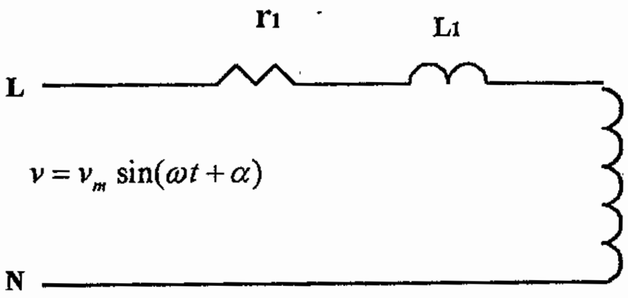


Figure 3 Primary equivalent circuit of a transformer.

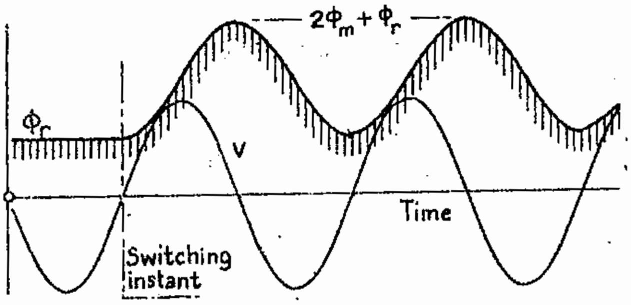


Figure 4 Flux waveform when voltage is applied at zero instant and ϕ_r is positive [2].

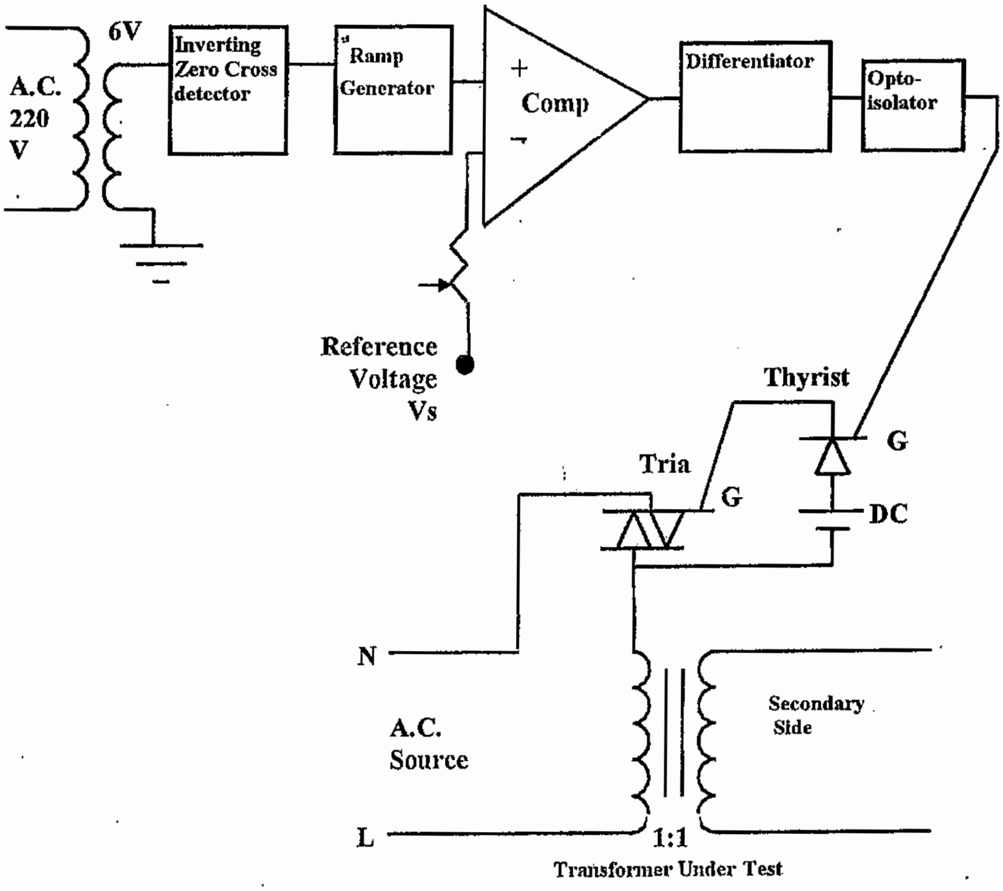
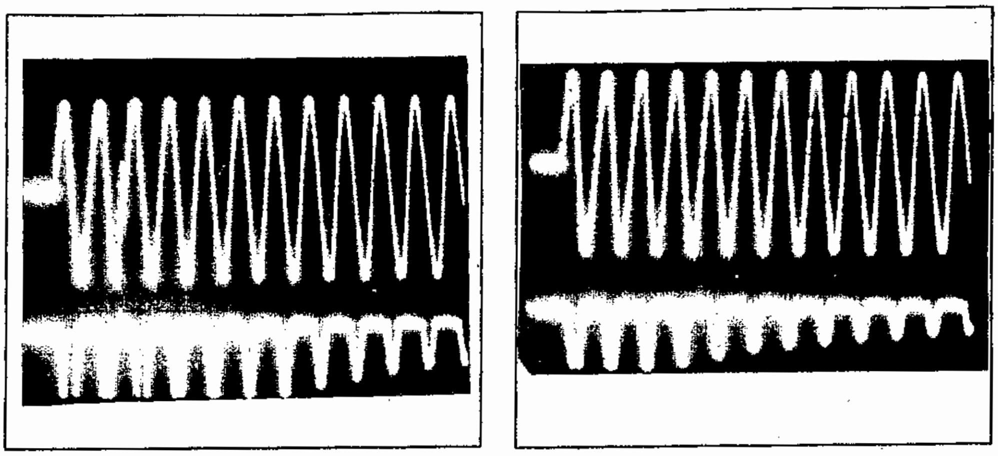


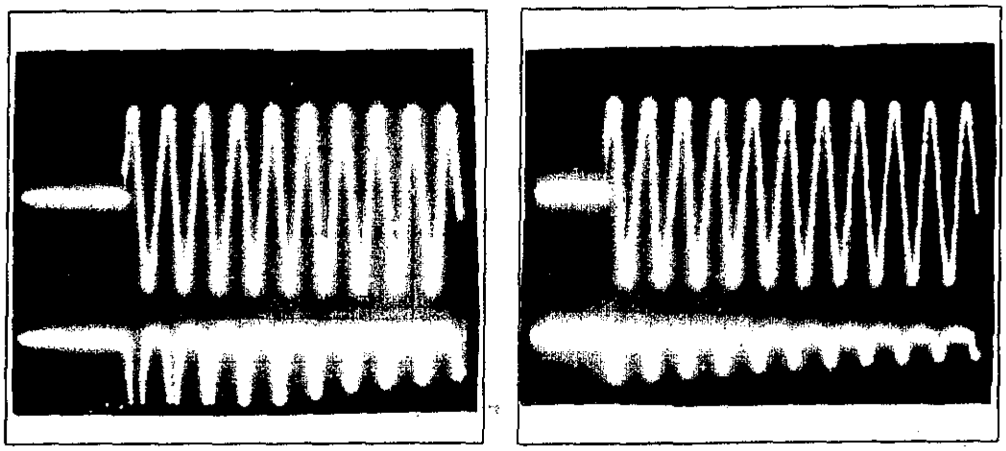
Figure 5 Proposed Triggering Circuit Block Diagram.



(a) without introducing the circuit.

(b) after intruducing the circuit

Figure 6 Oscillogram of the supply voltage and magn. current waves at an angle $\alpha=0$.
(Scales: Supply voltage 5V/Div., Magn. Current 0.1A/Div., 20ms/Div.)

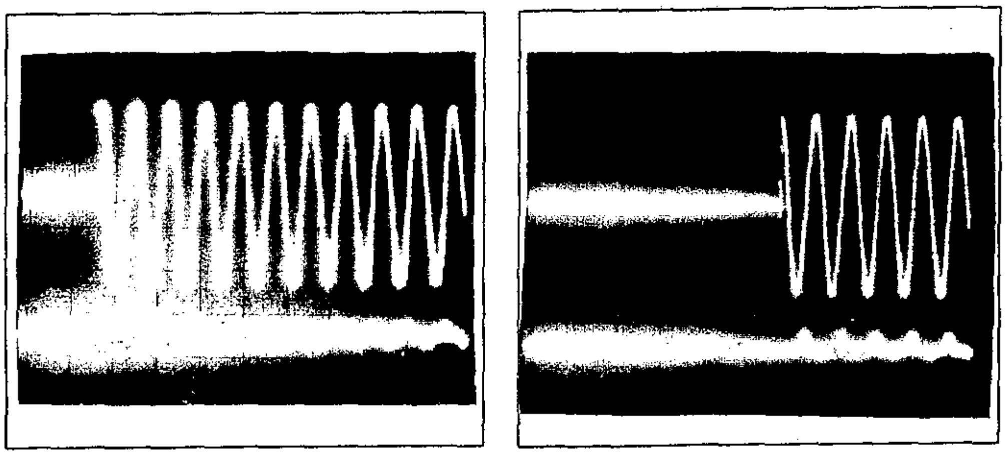


(a) without introducing the circuit.

(b) after intruducing the circuit

Figure 7 Oscillogram of the supply voltage and magn. current waves at an angle $0<\alpha<\pi/2$.

(Scales: Supply voltage 5V/Div., Magn. Current 0.1A/Div., 20ms/Div.)

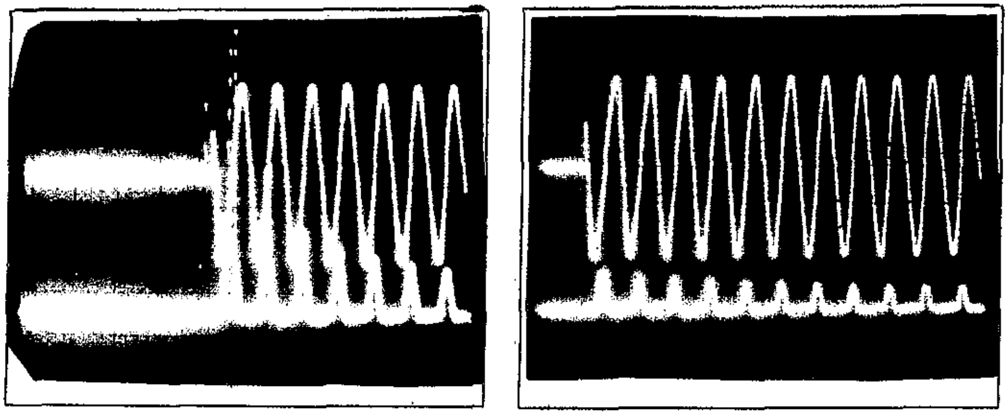


(a) without introducing the circuit.

(b) after intruducing the circuit

Figure 8 Oscillogram of the supply voltage and magn. current waves at an angle $\alpha=\pi/2$.

(Scales: Supply voltage 5V/Div., Magn. Current 0.1A/Div., 20ms/Div.)

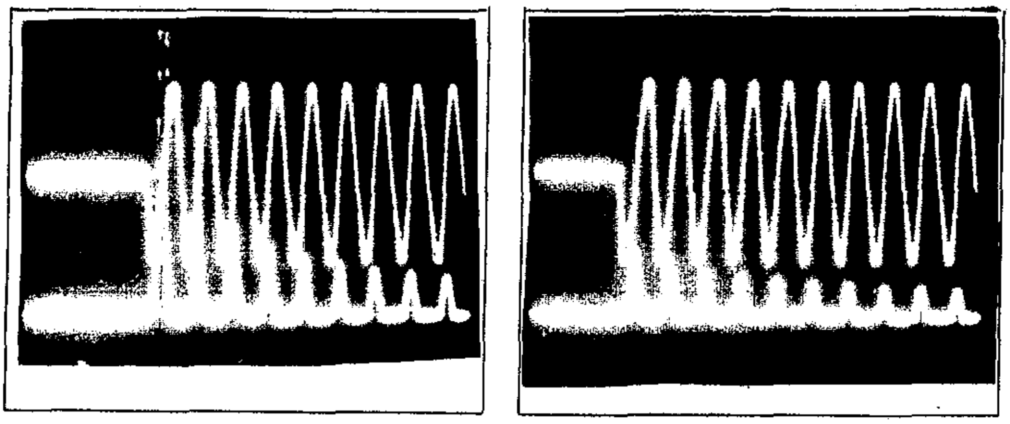


(a) without introducing the circuit.

(b) after intruducing the circuit

Figure 9 Oscillogram of the supply voltage and magn. current waves at an angle $\pi/2<\alpha<\pi$.

(Scales: Supply voltage 5V/Div., Magn. Current 0.1A/Div., 20ms/Div.)

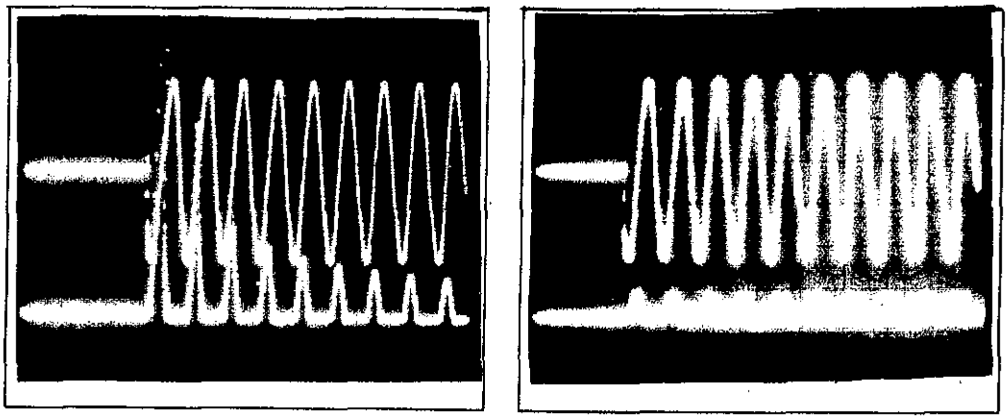


(a) without introducing the circuit.

(b) after intruducing the circuit

Figure10 Oscillogram of the supply voltage and magn. current waves at an angle $\alpha=\pi$.

(Scales: Supply voltage 5V/Div., Magn. Current 0.1A/Div., 20ms/Div.)

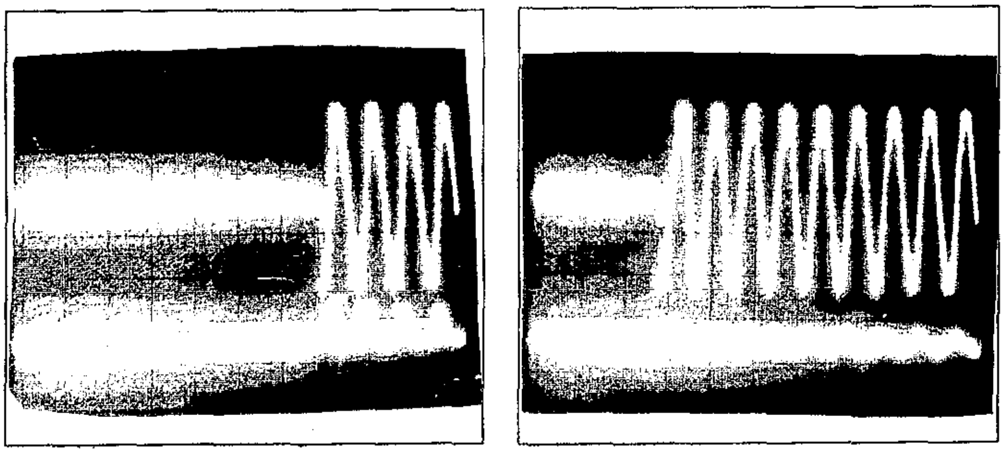


(a) without introducing the circuit

(b) after intruducing the circuit

Figure11 Oscillogram of the supply voltage and magn. current waves at an angle $\pi<\alpha<3\pi/2$.

(Scales: Supply voltage 5V/Div., Magn. Current 0.1A/Div., 20ms/Div.)

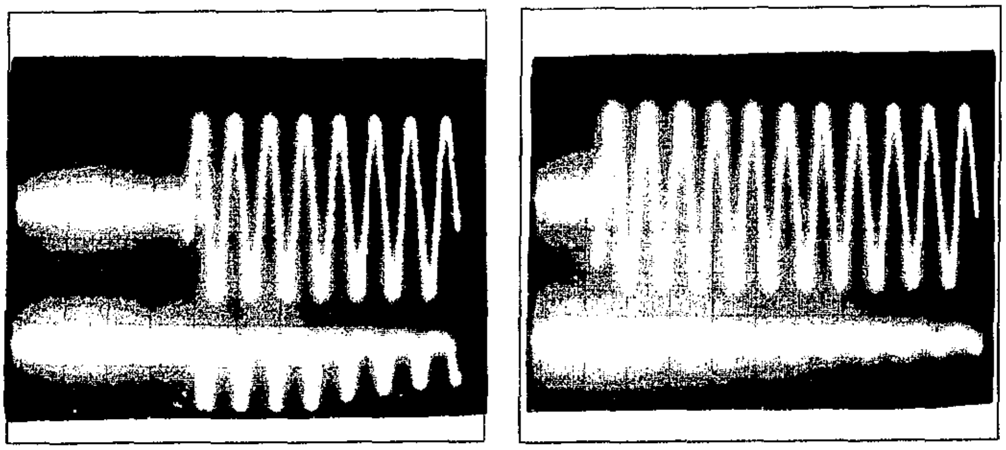


(a) without introducing the circuit.

(b) after intruducing the circuit

Figure12 Oscillogram of the supply voltage and magn. current waves at an angle $\alpha=3\pi/2$.

(Scales: Supply voltage 5V/Div., Magn. Current 0.1A/Div., 20ms/Div.)



(a) without introducing the circuit.

(b) after intruducing the circuit

Figure13 Oscillogram of the supply voltage and mag. current waves at an angle $3\pi/2<\alpha<2\pi$.

(Scales: Supply voltage 5V/Div., Magn. Current 0.1A/Div., 20ms/Div.)

تقليل التيار الممغنط المتدفق العابر في المحولات باستخدام دائرة تشغيل إلكترونية

عبدالسلام سعيد الغامدي
الكليه التقنيه بجده

المستخلص:

يتطرق هذا البحث إلى تحديد أسباب وعلاج ظاهرة التيار الممغنط المتدفق العابر في المحولات. يتضمن هذا البحث تحليلا رياضيا للتيار المتدفق، وذلك لإيجاد أفضل لحظة تشغيل للمحول. لقد تم تصميم دائرة تشغيل إلكترونية يمكن ضبطها لتشغيل المحول عند لحظة تشغيل منتقاة، تعتمد على خواص المحول. كما تم اختبار عمل الدائرة على محول حقيقي. تمت مناقشة الرسوم التذبذبية لأشكال التيار الممغنط وذلك قبل وبعد استخدام دائرة التشغيل الإلكترونية. لقد تم الخلوص إلى أن دائرة التشغيل تلك قد خفضت قيمة التيار المتدفق بصورة ملحوظة.