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Electronic System for Reduction of Transient Inrush Current in Transformer

Jiri Hammerbauer[1], Milan Stork[2]
[1] Department of Electronics and Information Technology/RICE, University of West Bohemia, Plzen, Czech Republic
[2] Department of Electronics and Information Technology/RICE, University of West Bohemia, Plzen, Czech Republic
hammer@fel.zcu.cz, stork@fel.zcu.cz

Abstract

This paper introduces a methodology to investigate controlled switching (or "Point on Wave Switching") to reduce magnetizing inrush current in Transformer. When transformer is switched on, transformer will get energized and transiently, large current flows through the primary winding. This mentioned current is - transient inrush current and it may raise up to ten times (or more) the nominal current of transformer during operation. Though transient inrush current lasts within few cycles, it has some bad effects e.g. problems with operations of protective devices, production of mechanical stress to the transformer core, power system quality, problems with sensitive electrical loads such as medical equipment and computers connected to the grid. Hence decreasing of transient inrush currents is important. The method using controlled switching means connect transformer at the correct phase voltage waveform to achieve the minimum inrush current. This reliable method was chosen to prevent generation of high magnitude inrush current. The non expensive electronic system for inrush current decreasing for single phase transformer switching on was developed and successfully tested in practical use.

Keywords: *Inrush current, Pulse width, Monostable pulse generator, Microcontroller, Power switch, Remanent magnetic flux, Transformer, Triac.*

1. Introduction

Inrush current is in response to saturation of the transformer magnetic circuit caused by transient phenomenon that occurs after transformer is connected to power grid. Remanent magnetic flux changes gradually to magnetic flux in steady state during energization. This is why the transformer significantly reduces its impedance and takes multiply higher magnetizing current from power grid.

A high inrush current can cause several issues for the system like component failure (fuse, bridge diode, etc.) but also represents an excessive current stress on the power grid compared to the nominal current sensed in steady state. Indeed, if nothing is implemented to limit the inrush current, the start-up current can easily be 10 to 20 times higher than the steady-state current. The power grid wires and other current protection components have then to be rated to deliver such high current for a short time. Moreover, the sudden current variation will lead to Line voltage dips. These fluctuations will decrease the power delivered to other loads. Then lamps or displays connected on the line could show brightness variation called the flicker phenomenon. To avoid such unwanted phenomenon, the IEC 61000-3-3 Electromagnetic standard defines the maximum voltage fluctuation which can be accepted, and so the maximum repetitive current, according to the application case.

Various ways of limiting the inrush current of a transformer have been described in the literature, sometimes even with a necessary transformer modification (e.g. air gap increasing), or with expensive accessories. Methods that require intervention in the structural arrangement of the transformer, or require significant funds for additional instrumentation are described in [1 – 9]. Modeling related to the inrush current of transformers is described, for example, in [10 – 16]. In the literature [17 - 20] methods based on controlled switching are described. The method of controlled switching on and the implementation of this method is described in this work. The main advantage of this method is that there is no need to modify the transformer or add additional circuits to the transformer.

This paper does not provide in-depth theoretical analysis, but describes a practical approach to limiting the inrush current without any transformer modification. The implemented electronic system is not expensive and allows the use of a triac or relay as a power switch to turn on the transformer. The proposed system was successfully tested on several single phase transformers, both with an EI core and with a toroidal core. The results are presented.

2. A short overview of known methods related to limiting the inrush current of transformers

Generally, there are two approaches for limiting inrush current:

- A. Change in internal structure of the transformer:
    - Change in magnetic characteristic of the transformer core.
    - Change in winding structure of the transformer.
- B. Adding impedance to the primary side of the transformer and/or extra control circuits to the transformer:
    - Adding circuits in order to control the switching angle.
    - Adding circuits to control sequential switching of the phases.
    - Superconducting inrush current limiter.

2.1. Neutral Earthing Resistors

Optimal neutral resistor on the transformer can significantly reduce the inrush current magnitude and duration. The neutral earthing resistor limits the current going through the neutral which in turn controls the inrush of current during the first and second phase energization.

2.2. Pre – Insertion of resistors

Resistors are typically inserted into the capacitor – energizing circuit for 10 – 15msec prior to the closing of the main contacts, through the closing of an additional set of contacts. Synchronisation between the resistor and the main contact is required and is usually achieved by connecting the resistor contact rod directly to the main contact control rod. Once the switching has been achieved, the resistor is then switched off from the circuit.

2.3. Controlled Switching

The high inrush current can lead to the mal – operation of relays and other protecting devices. With this result, there are chances of high mechanical stress on to the transformer winding due to the magnetic forces and can result in power quality issues. The use of resistors can only reduce the magnitude of inrush currents, whereas the use of controlled switching technology can limit the inrush current to greater extend. This strategy is also known as Point – On Wave Controlled Switching. In this method, simply the transformer will be energized phase by phase at the corresponding voltage peak. This strategy of switching seems to be accurate and reliable. However, the drawback of such a mechanism is the cost involved in the implementation of the technique. The practical power system employs the use of gang operated circuit breakers. When using the point – on wave switching strategy, the circuit breakers are needed to be replaced with single pole circuit breakers. This paves the way for the three pole switching strategy. This is done by using a gang operated circuit breaker, a control circuit to monitor the voltage waveform and send a closing signal to main pole at the zero crossing of the voltage waveform. The other poles are mechanically linked to the main pole and are staggered by 120˚ apart so that all poles are closed at the zero crossing of the voltage waveform.

2.4. Our solution

Without any intervention in the transformer and without complex additional circuits, the solution is only suitable switching on. Developed for transformers up to several kVA that can be switched by relay or triac. It is not necessary to know the transformer model or type - toroid (The toroidal transformer) or E sheets The literature often describes measurement methods, the influence of the type and properties of transformer plates, but not simple solutions

3. Theoretical background

This chapter briefly presents the basic mathematical relationships concerning the voltage and magnetic flux of the transformer, which are generally known [10 - 16]. Assuming that the applied voltage at primary of transformer is $v(t)$, which can be described as follows:

$$v(t) = V_{\mathrm{m}} sin(\omega t + \alpha) = \sqrt{2} \cdot V_{ef} sin(\omega t + \alpha) \tag{1}$$

here V_m is amplitude and V_{ef} is effective voltage. According to Faraday's law, the induced voltage and flux $\Phi(t)$ derivative are given by the relation

$$v_i(t) = -N \frac{d\Phi(t)}{dt} \tag{2}$$

where N is the number of turns of the primary side windings

After substituting equation (1) into Faraday's law of induction and integration

$$\frac{V_m}{N} \int sin(\omega t + \alpha) dt = -\Phi(t) \tag{3}$$

It comes out after integration of left part of (3)

$$-\frac{V_m}{N\omega} cos(\omega t + \alpha) + C = -\Phi(t) \tag{4}$$

The initial condition at time $t = 0$ is given by the remanent magnetic flux $\Phi(0) = \Phi_r$ therefore

$$-\frac{V_m}{N\omega} cos(\alpha) + C = -\Phi_r \tag{5}$$

So constant C is

$$C = \frac{V_m}{N\omega} cos(\alpha) - \Phi_r \tag{6}$$

The resulting magnetic flux after switching on the transformer then has a course

$$\Phi(t) = \frac{V_m}{N\omega} \left[cos(\omega t + \alpha) - cos(\alpha) \right] + \Phi_r \tag{7}$$

Respectively

$$\Phi(t) = \frac{V_m}{N\omega} \left[sin(\omega t + \alpha + \frac{\pi}{2}) - cos(\alpha) \right] + \Phi_r \tag{8}$$

The relation (8) can be rewritten as

$$\Phi(t) = \frac{V_m}{N\omega} sin(\omega t + \alpha + \frac{\pi}{2}) - \frac{V_m}{N\omega} cos(\alpha) + \Phi_r = \Phi_m sin(\omega t + \alpha + \frac{\pi}{2}) - \Phi_m cos(\alpha) + \Phi_r \tag{9}$$

The previous equation (9) can be split on periodic AC part and transient DC part

$$\Phi(t) = \underbrace{\Phi_m cos(\omega t + \alpha)}_{AC} \underbrace{- \Phi_m cos(\alpha) + \Phi_r}_{DC} \tag{10}$$

Thus, during the transient, there is a direct current component of the magnetic flux (DC part), which depends on the time moment of connection of the transformer to the network with immediate phase α and with the remanent magnetic flux Φ_r. The steady state magnetic flux AC is superimposed on transient DC component. The ideal case is when the DC component will be minimal (no transient occurs)

$$\Phi_m cos(\alpha) - \Phi_r = 0 \tag{11}$$

E.g. for $\Phi_r = 0$, optimal $\alpha = \pi/2$, but for $\Phi_r \neq 0$ the optimal α is

$$\alpha = arccos\left(\frac{\Phi_r}{\Phi_m} \right) \tag{12}$$

The worst case, on the other hand, occurs when $\alpha = 0$ and $\omega t = \pi$ and the remanent magnetic flux $\Phi_r < 0$

$$\Phi_{MAX} = \Phi_m cos(\pi) - \Phi_m cos(0) + \Phi_r = -2\Phi_m + \Phi_r \tag{13}$$

Relationships (10) - (12) are especially important for further considerations. It follows from relation (11) that also for a transformer with non-zero remanent magnetism there is an optimal switching angle α, which is, however, influenced by the value of the remanent magnetism of a particular transformer.

4. Electronic system for reduction of magnetizing inrush current in transformer

This section describes the electronic system (ES), which is based on method using controlled switching which means switch on the transformer at the correct phase voltage waveform. It should be noted that each ES is set for a specific transformer. The ES principle is as follows. First, the optimum delay T_w for switching on the transformer is found using the measuring electronic system (MES) and then the application electronic system (AES) is used for the application. The ES are therefore 2, the first - universal for measurement and setting (it is necessary to find the optimal phase for switching on the transformer, i.e. the optimal value of the pulse width T_W generated by the monostable pulse generator), the second - application system which is set for a specific transformer. It should be added that changing MES to AES is very simple, because it is only a matter of removing a few components (blocks). The block diagram of MES is shown in Fig. 1. Fig. 2 shows the time course of signals in MES and AES. If a triac is used as a power switch, the transformer will be disconnected when the current passes through zero. The block diagram of AES is shown in Fig. 3 (bordered by dashed lines).

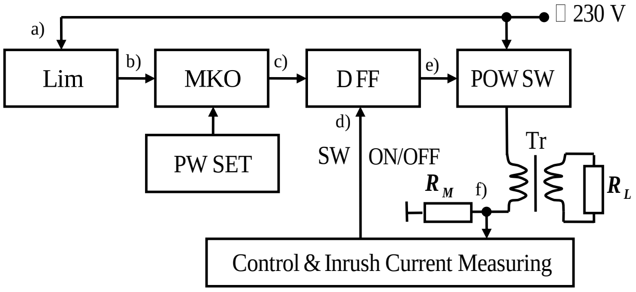

Fig. 1 Block diagram of MES. Lim - Voltage limiter, MKO - Monostable pulse generator (monostable multivibrator), DFF- D Flip flop, POWSW - Power switch, PW SET - Pulse width setting, Tr - Measured transformer, SW- ON/OFF signal (switch), Control & Inrush current measuring block, R_M - Current measuring resistor, R_L - Load resistor, a) ÷ f) signals which are shown in Fig. 2

The procedure for setting up the MES system is as follows:
The MES system is periodically switched on/ff by the SW switch and the minimum value of the inrush current is set by changing the pulse width T_W, The inrush current is read on the measuring resistor R_M and displayed on the oscilloscope.

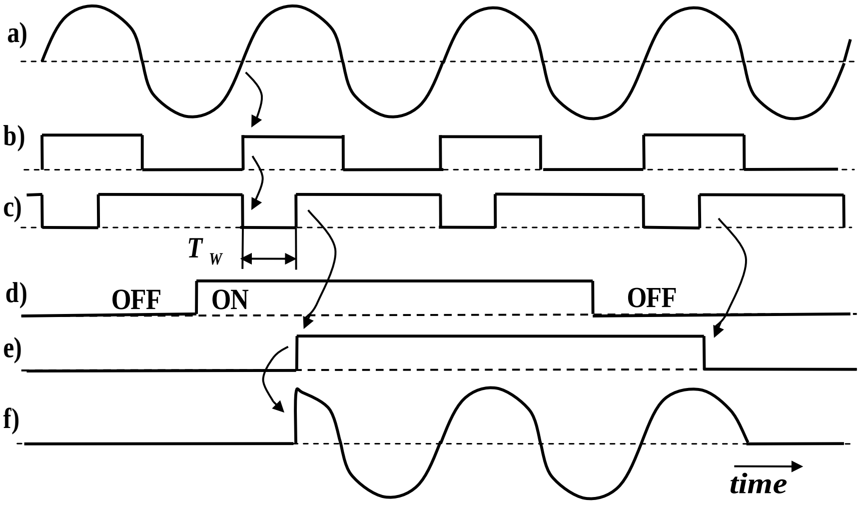

Fig. 2. Time courses of signals. From top to bottom: a) Mains voltage, b) Limited mains voltage, c) A pulse of width T_w generated by a monostable pulse generator at the leading edge of the limited signal b, d) Desired transformer on / off signal applied to the D input of the D-flip-flop, e) D-Flip-flop output signal. The output signal status changes only at the leading edge of the signal from the monostable pulse generator. This signal is used to control the power switch, f) the signal on measuring resistor R_M

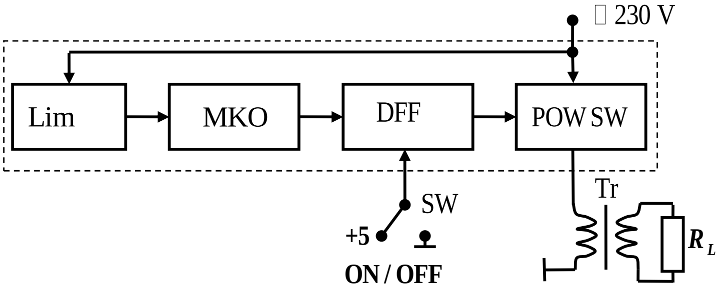

Fig. 3. Block diagram of AES system. Lim - Voltage limiter, MKO - Monostable pulse generator, DFF - D Flip flop, POW SW - Power switch, Tr - transformer, SW- ON/OFF switch, R_L - Load resistor

A detailed diagram of the system with triac used as a power switch is shown in Fig. 4. The MES system is periodically switched on/off by the SW switch and the minimum value of the inrush current, which is measured at R_{11}. Inrush current is set by width of T_W therefore changing the resistor R_4. R_{11} is measuring resistor for current measurement during setting of optimal pulse width T_W (in MES system). After setting the optimal pulse width T_W for a specific transformer, the resistor R_{11} = 0 (AES system). The system with relay is presented in Fig. 5.

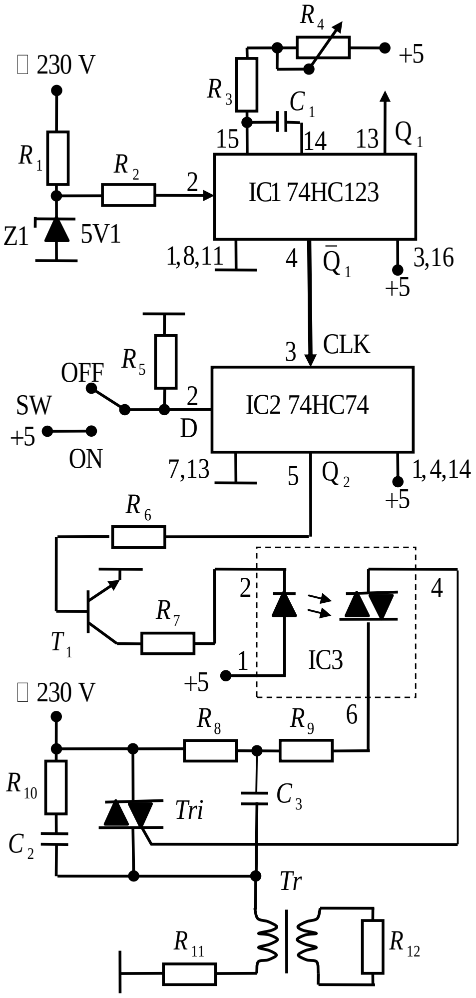

Fig. 4. Detailed diagram of the system with triac. IC1 - 74HC123, IC2 - 74HC74, IC3 - MOC3023, Z1 - Zener. Diod 5V1, T1 - BC156, Tri - Triac BTA 140/800, C_1=15n, C_2=10n, C_3=47n, R_1=M1, R_2=56k, R_3=5k6, R_4=1M, R_5=10k, R_6=150, R_7=390, R_8=390, R_9=470, R_{10}=39, R_{11},R_{12} - according Tr, Tr - tested transformer

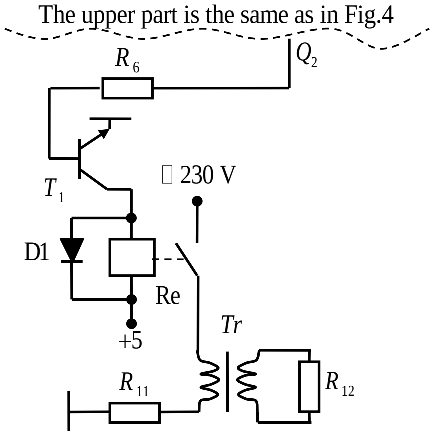
The upper part is the same as in Fig.4

Fig. 5. The part of diagram of the system with relay. R11 is measuring resistor, for application R11=0. The values of the components remain the same as in the diagram according to Fig. 4

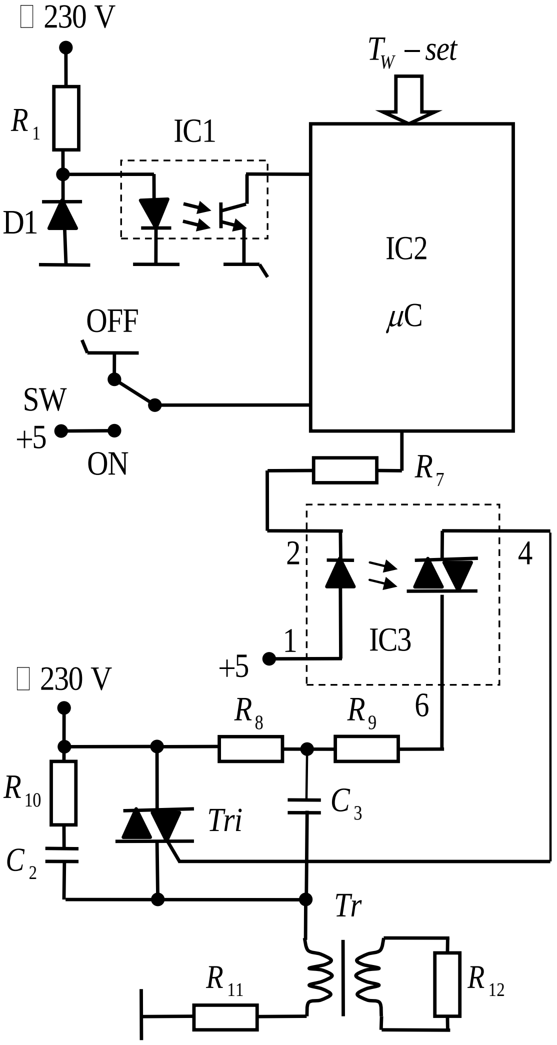

Fig. 6. The circuit diagram - solution based on microcontroller. Two grounds are used - power ground ⊥ and microcontroller ground ┴ . The values of the components remain the same as in the diagram according to Fig. 4

5. Microcontroller solution

This chapter describes the solution using a microcontroller (µC). Most of the electronic circuits that are used, for example, in Fig. 4, can be replaced by a µC. These are circuits processing input signals and generating an output signal to turn on the transformer. The diagram of the system with is in Fig. 6. This system is galvanically isolated from the mains using optocouplers. The power part of the system is of course the same as in the case of a system made of discrete components. For construction µC STM32F303x6/x8 NUCLEO [21 - 23] was used, but any type of µC can be used as well.

6. Experimental results

This chapter presents the results of the inrush current of the transformer for switching at zero voltage and then for the optimal moment of switching on. 3 different transformers were measured, one transformer with E core and 2 toroidal transformers. The measurement results are presented only for a toroidal transformer with a power of 300 VA. The goal was to achieve the minimum current peak when switching on the transformer.

It was confirmed that with the same method of switching off, the remanent magnetism remains constant for a long time even with a longer time of switching off the transformer (several weeks) and the switching current of the transformer can be minimized. Fig. 7 shows the time diagrams of the signals during two turn-on-turn-off of the transformer without minimizing the inrush current. The recording of signals from the oscilloscope was also saved in CSV (Comma-Separated Values) format. The course of the signals (zoom) was then displayed using MATLAB, see Fig. 8.

Fig. 9 shows the time diagrams of the signals during two turn-on-turn-off of the same transformer as was shown in Fig. 7 and 8, but with minimizing the inrush current. Zoom is presented in Fig. 10. From these figures it can be seen that the inrush current of the transformer is considerably smaller.

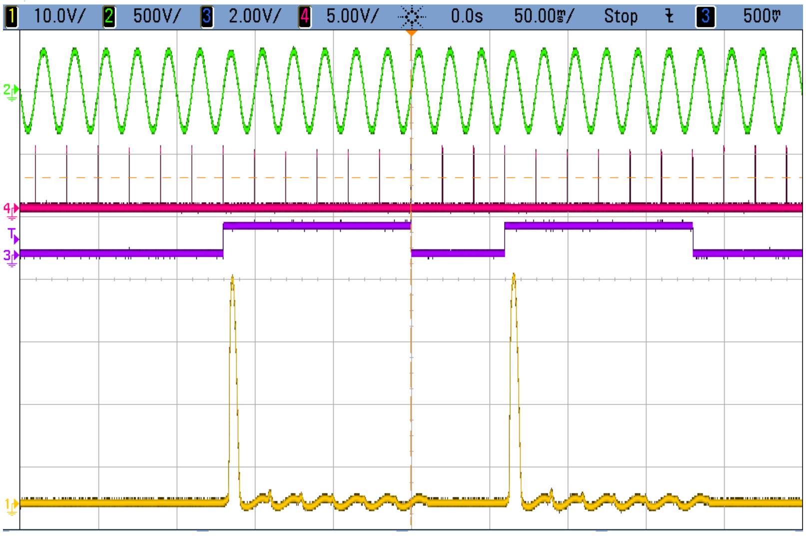

Fig. 7. A copy of the oscilloscope screen. The time diagrams of the signals during two turn-on-turn-off of the transformer without minimizing the inrush current. From top to bottom: Mains voltage (Line voltage), Output of Monostable flip-flop (pulses generated when the mains voltage crosses zero during a positive half-wave), Output of D flip-flop (at level H, the transformer is turned on, at level L, the transformer is turned off), Ip - the course of the current through the primary winding

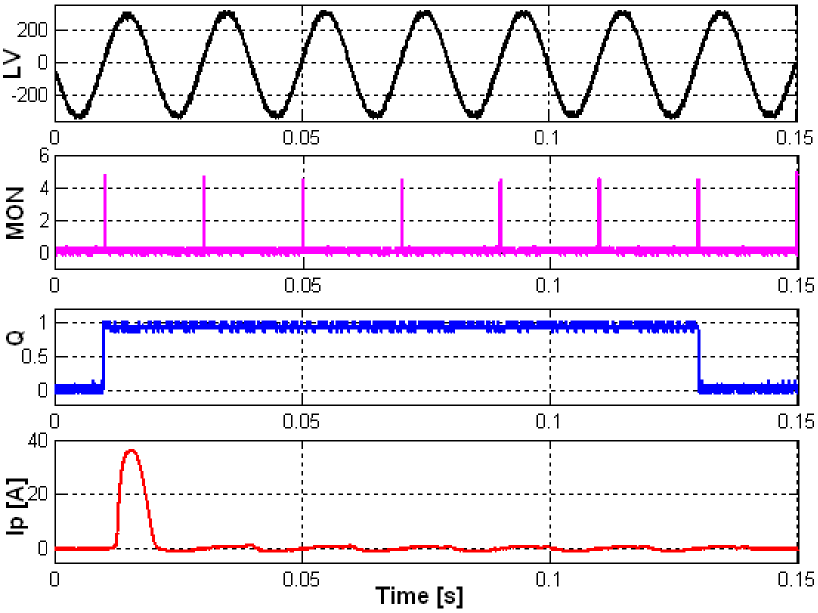

Fig. 8. Zoom of Fig. 7. The time diagrams of the signals during two turn-on-turn-off of the transformer without minimizing the inrush current. From top to bottom: LV - Mains voltage (Line voltage), MON - Output of Monostable flip-flop, Q - Output of D flip-flop, Ip - the course of the current through the primary winding

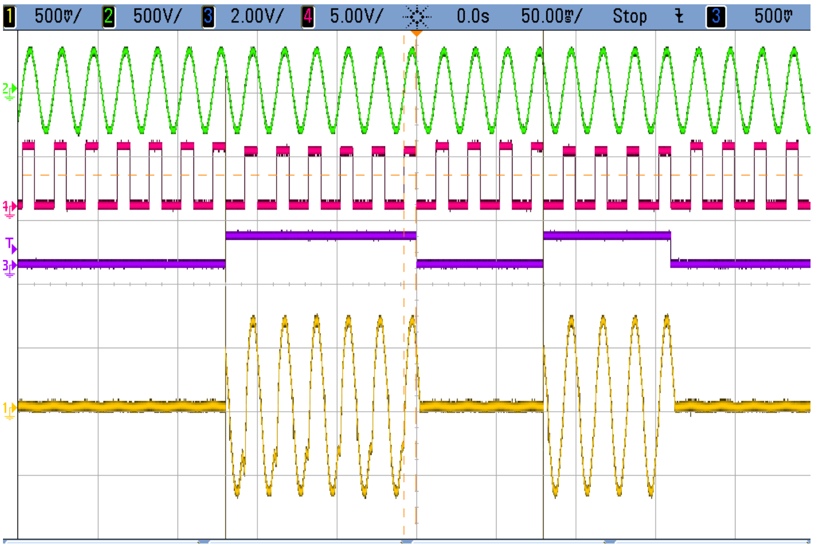

Fig. 9. A copy of the oscilloscope screen. The time diagrams of the signals during two turn-on-turn-off of the transformer with minimizing the inrush current. From top to bottom: Mains voltage (Line voltage), Output of Monostable flip-flop, Output of D flip-flop, Ip - the course of the current through the primary winding

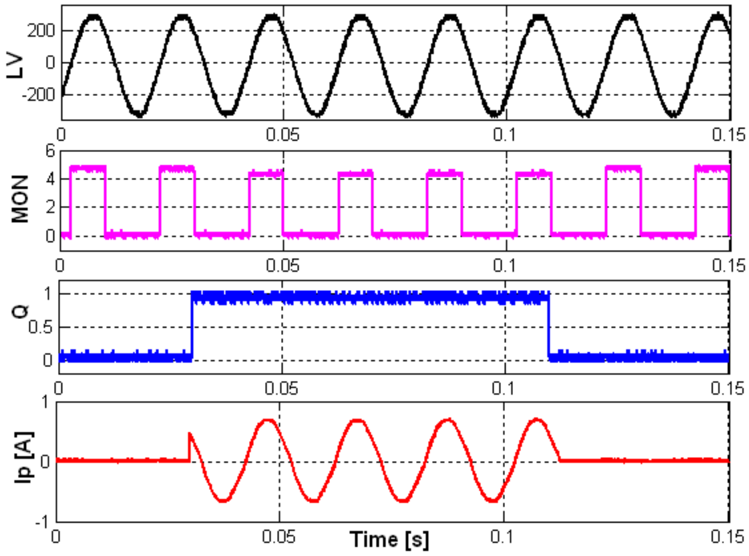

Fig. 10. Zoom of Fig. 9. The time diagrams of the signals during two turn-on-turn-off of the transformer with minimizing the inrush current. From top to bottom: LV - Mains voltage (Line voltage), MON - Output of Monostable flip-flop, Q - Output of D flip-flop, Ip - the course of the current through the primary winding

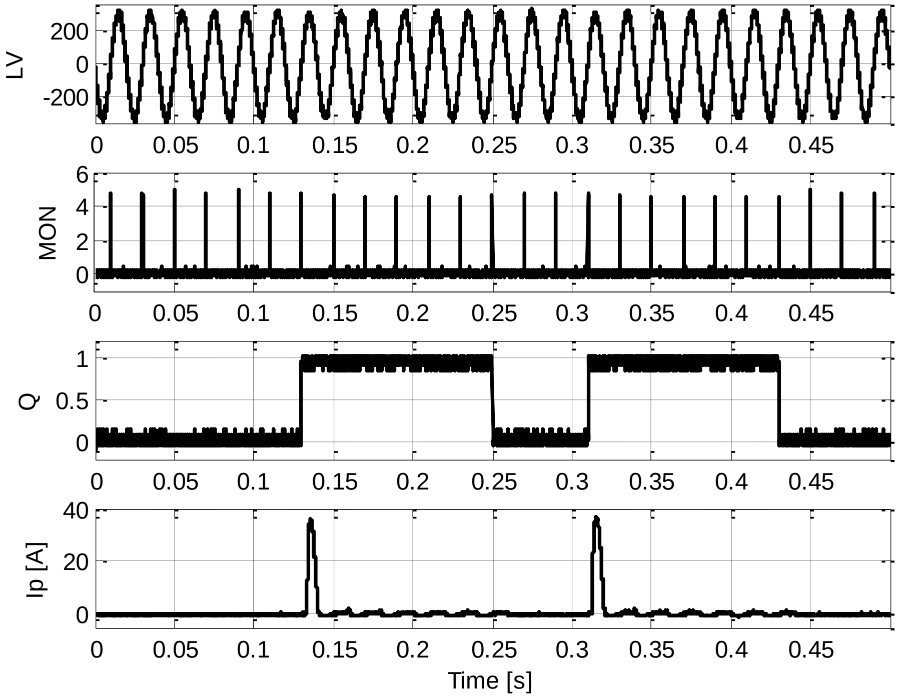

Fig. 11. A copy of the oscilloscope screen. The time diagrams of the signals during repeated turn-on-turn-off of the transformer without minimizing the inrush current. From top to bottom: Mains voltage (Line voltage), Output of Monostable flip-flop (pulses generated when the mains voltage crosses zero during a positive half-wave), Output of D flip-flop (at level H, the transformer is turned on, at level L, the transformer is turned off), Ip - the course of the current through the primary winding. Inrush current peak is greater than 35 A

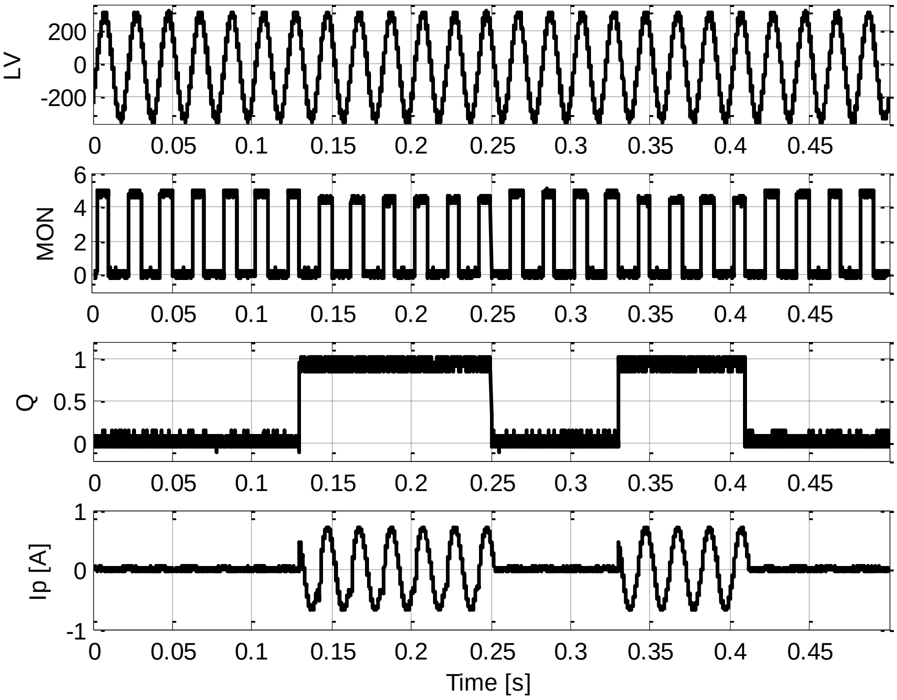

Fig. 12. A copy of the oscilloscope screen. The time diagrams of the signals during two turn-on-turn-off of the transformer with minimizing the inrush current. From top to bottom: Mains voltage (Line voltage), Output of Monostable flip-flop, Output of D flip-flop, Ip - the course of the current through the primary winding. This figure is a modification of Fig. 11. It is the same system but with optimal transformer switching on

7. Conclusion

Many articles have been published on transformer inrush current problems, but much less on specific solutions to this problem. This article described a simple, non expensive, but effective system that can be used to minimize transformer inrush current. The method using controlled switching was used which means switch on the transformer at the correct phase voltage waveform. Another advantage is that the realized system can be used for any type of transformer without having to know its characteristics in detail. A solution made of discrete components was intentionally presented, which shows the principle of the system's function and also the solution using a microcontroller was shown. Both variants were implemented and verified on several transformers. The results of measurements performed on one of the transformers were presented. The advantage of the solution presented in the article is that it is reliable and simple.

The solution presented in this article is based on a single-handed system that connects the transformer at the appropriate moment due to the remanent magnetism that remains in the transformer. Since the transformer is always disconnects at the same instant (with respect to the mains voltage), the remanent magnetism is also the same. This makes it possible to find the optimal switching time with minimum inrush current. The device was used in a medical application, where there was a problem with repeatedly connecting the device with a transformer, which then generated current spikes that interfered with sensitive devices, such as ECG system.

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J. Hammerbauer, received the MSc. degree in Institute of Technology, Pilsen in 1989 and Ph.D. 1999 in Applied Electronics, Univ. of West Bohemia, Pilsen, He became as Associate Professor in 2003 He is head of the department " Electronics and Information Technology. Research and expertise: Development of DC/DC converters with high efficiency and small dimensions, and controlled switched current converters for high luminance LEDs. Design and development of mains driven power supplies with emphasis on high efficiency, small size, high switching frequency, wide range of input voltage, reliability, and EMC. Development of chargers for all types of accumulators, especially of modern Li-ion and Li-pol types. Development of methods and systems for the measurement and diagnostics of standby power supplies used in consumer and industrial electronics (UPS systems). Research and design of electronic control systems for modern methods of accumulation of energy generated by photovoltaic cells, .e.g. by means of super and ultracapacitors. AC and DC current regulators.

M. Stork received the M.Sc. degree in electrical engineering from the Technical University of Plzen, Czech Republic at the department of electronics in 1974 and Ph.D. degree in automatic control systems at the Czech Technical University in Prague in 1985. In 1997, he became as Associate Professor at the Department of Electronics and Information Technology, faculty of electrical engineering on University of West Bohemia in Plzen, Czech Republic and full professor in 2007. He has numerous journal and conference publications. He is member of editorial board magazine "Physician and Technology". His research interests include analog/digital systems, signal processing and biomedical engineering.