J. Bauer, P. Ripka, K. Draxler, R. Styblikova: Demagnetization of Current Transformers, IEEE Trans Magn Volume: 51 , Issue: 1 , Part: 1 DOI: 10.1109/TMAG.2014.2356574 Publication Year: 2015 , Article#: 4000604

Demagnetization of Current Transformers Using PWM Burden

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Current transformers (CTs) show large errors when they are magnetized by dc current. This error can be reduced after proper demagnetization. One of the methods to demagnetize the CT is to increase the core flux by increasing its burden. The burden should be adjusted according to the measured ac current. In this paper, we show that pulsewidth modulation switchable resistor can be used as variable burden for this application. This method enables to restore the nominal precision of the heavily magnetized CT from 2.5% back to 0.2% without interruption of the CT operation.

***Index Terms*—Current transformer (CT), lock-in amplifier, pulsewidth modulation (PWM).**

I. INTRODUCTION

CURRENT transformers (CTs) are susceptible to remanence caused by dc magnetization. In such case, the precision of the CT can be seriously degraded especially at low measured currents [1]–[4]. Magnetization can be caused by temporary unipolar transients from lightning or switching of power devices to the supply grid. When the CT operates at >80% of its nominal current I_N, the CT is spontaneously demagnetized. For lower measured ac current the CT remains permanently magnetized. This effect can cause large errors especially when measuring energy transferred in unloaded supply network. The origin of this error is that magnetized core has lower apparent permeability [2].

Method for measuring the dc component of the current using fluxgate effect in the CT was described in [5]–[7]. The dc current can be compensated to restore the CT precision [8], [9]. These methods can also be used to demagnetize the CT and keep it without remanence. However, the instrumentation is complicated and requires an additional source of power [10]. The aim of this paper is to develop a simple device for demagnetizing the CTs in the field.

The magnetized CT can be demagnetized by increasing the measured current, e.g., to 120% of the nominal value I_N and slowly decreasing it to zero. This is easy in the lab, but not very practical when implemented in a network. Another technique consists in increasing the burden so as to increase the voltage at the ends of the secondary winding and therefore the magnetic flux in the core. For a measured current of 0.1 I_N the required increase or the burden is theoretically 12 times R_N. The transient from switching the burden back to R_N should be controlled to prevent another magnetization. In some cases this is not trivial.

This paper is organized as follows. In Section II, we first show that by increased burden we are able to effectively demagnetize CT so that resulting error is very similar to CT demagnetized by conventional method.

Then, we describe and discuss two methods how to adjust R_2. Section III describes in detail the principle of the pulsewidth modulation (PWM) switched resistor method, which was selected for our device. In Section IV, we experimentally verify the proposed method.

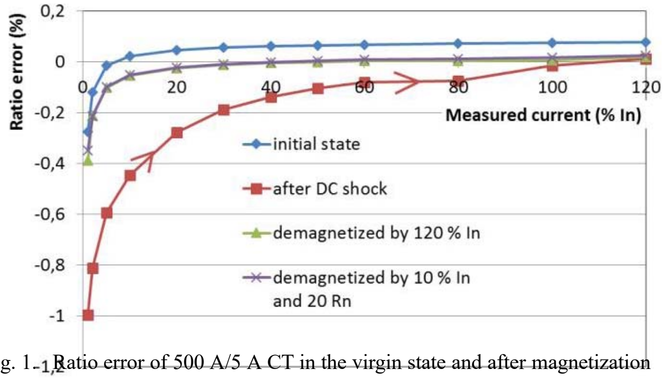

Fig. 1. Ratio error of 500 A/5 A CT in the virgin state and after magnetization to remanence and two methods of demagnetization.

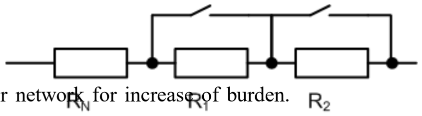

Fig. 2. Resistor network for increase of burden.

II. DEMAGNETIZATION METHODS

Fig. 1 shows the ratio (amplitude) error of the class 0.2 CT with 500 A/5 A ratio. The core of this transformer is made of high-permeability oriented Si–Fe. The perfectly demagnetized CT has ratio error <0.2% in the wide range from 2% to 120% I_N. After magnetization by large dc current to the remanence this transformer is out of its accuracy class for $I < 30\%$ I_N. Only after $I > 80\%$ I_N, the core slowly starts to demagnetize. We magnetized the transformer again and demagnetized it by manually increasing the burden to 20 R_N at 10% I_N. The quality of demagnetization is very similar as before; although it is not ideal, the CT specs are again met.

For real application R_2 should be adjusted according to the actual value of I_1. We can either use conventional switched network of weighed resistors (Fig. 2), or PWM of switched resistor (Fig. 3).

Resistor network is a simple solution, but it has a substantial problem for fine resistance adjustment it needs six to eight switches, which brings large uncertainty caused by

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Digital Object Identifier 10.1109/TMAG.2014.2356574

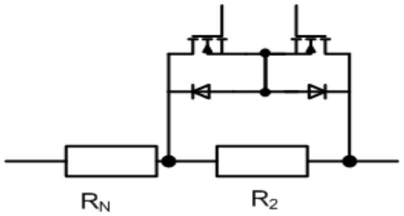

Fig. 3. PWM switched resistor.

switch ON-resistances. The second method requires more complicated control logic, but allows fine adjustment with single switch. In this paper, we therefore verify the demagnetization by PWM switched resistor.

III. PWM Switched Resistor

The development of the semiconductor devices and improvement of their parameters have already influence area of electric drives and energy conversion. However, a limiting parameter of these devices is the amount of heat that needs to be dissipated because the heat is proportional to the power losses caused mainly during the switching transition and the inner resistance of the semiconductor, switching of these devices was limited. Recent development in the area of MOS transistors has led to devices with very low resistance r_{DSon} in the range of 10 mΩ. Such devices can be used in circuits, where power electronics is needed and its influence should be negligible.

As stated previously, the burden value can be increased either by a resistor network or by PWM switched resistor. First, solution is simpler but requires more space and continuous change of the resistance is not possible. Therefore, we have focused on the PWM switched resistor solution. The PWM controlled variable resistor is already used in [11] as a damping resistor for protecting the power capacitor/passive power filter.

Because the secondary winding of the CT cannot be unloaded the solution shown in Fig. 2 was selected for PWM controlled resistor realization. The scheme is the same as in [12], but the switching scheme is different, whereas in [12] the switching time is the multiple of power line frequency, we used much higher frequency. The solution in [12] was developed for protective CTs, where accuracy is not critical parameter. Our solution was developed for instrument CTs.

In normal operation mode, both transistors are switched ON and the secondary current is according to its polarity flowing through one transistor and one antiparallel diode. When demagnetization of the CT is needed, PWM is enabled and transistors begin to be switched. Current then flows through the transistor when it is switched ON or through increased burden when the transistor is switched OFF.

The principle of PWM is well known from the semiconductor power converters, where PWM is employed for the generation of voltages with variable frequency and mean value. The mean value of the output voltage across one period can be calculated as

$$\bar{v} = \frac{1}{T_s}\int_0^{T_s} v(t)dt. \tag{1}$$

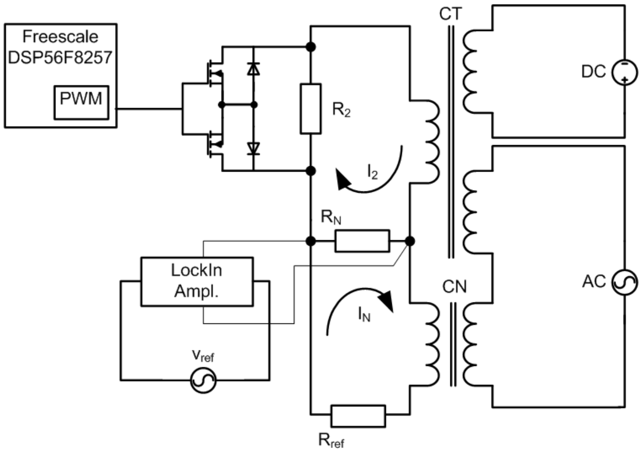

Fig. 4. Layout of the demagnetization device. CT converts the ac primary current I_1 into the secondary current I_2. CT is magnetized by momentary dc current I_{dc} injected into the auxiliary winding.

When we consider PWM principle and replace voltage by $R(t)$ that has value of r_{DSon} for $t \in [0,\ t_{\mathrm{ON}}]$ and R_2 for $t \in [t_{\mathrm{ON}},\ T_s]$, we can rewrite (1) into

$$\begin{aligned}\bar{R} &= \frac{1}{T_s}\int_0^{T_s} R(t)dt = \frac{1}{T_s}\left(\int_0^{t_{\mathrm{ON}}} r_{\mathrm{DS(ON)}}dt + \int_{t_{\mathrm{ON}}}^{T_s} R_2 dt\right)\\ &= \frac{t_{\mathrm{on}}}{T_s} r_{\mathrm{DS(ON)}} + \frac{t_{\mathrm{OFF}}}{T_s} R_2 \end{aligned} \tag{2}$$

where $t_{\mathrm{OFF}} = T_S - t_{\mathrm{ON}}$.

Because the r_{DSon} can be connected to the circuit during the normal operation of the CT, it can be included in the value of the burden. Equation (2) will be therefore simplified as

$$\bar{R} = \frac{t_{\mathrm{OFF}}}{T_s} R_2. \tag{3}$$

If the switching period T_S is several times shorter than the period of the measured current signal, the switching transition of the transistors can be neglected and the value of R_2 can be calculated according to (3). Equation (3) then define the value of equivalent resistance connected in series with the burden to demagnetize the transformer.

In analog technique, the PWM modulator can be realized as an operational amplifier that is comparing triangular carrier with variable threshold value. However, analog devices suffer from ageing, this is why analog solutions are replaced by digital solutions in a microprocessor.

IV. Experimental Validation of the Demagnetization of a CT Using a PWM Burden

For our experiment, we used a CT with transformation ratio of 500 A/5 A and real 5 VA nominal secondary burden, corresponding to a resistor of 0.2 Ω. The output of the transformer was loaded by sensing resistor $R_N = 0.1\ \Omega$. A VISHAY MPR resistor with value of 2 Ω was used as PWM switched resistor R_2. The CT errors were measured using a lock-in amplifier. Switching pulses for the transistors were generated by Freescale DSP56F8257 microcontroller. The period of PWM T_{CS} was 5 ms.

The experimental setup shown in Fig. 4 is used to implement the proposed CT demagnetization method and to determine the

TABLE I

MEASURED CT ERRORS

State of CT	Ratio error (%)	Phase displacement (“)
Initial error for $I_2 = 1$A	-0.24	-44
Magnetized CT	2.50	-172
Demagnetization for $R_2 = 2\ \Omega$	-0.15	-47
Magnetized CT	2.28	-190
Demagnetization by increased current $I_2 = 6$A	-0.12	-47
Initial error for $I_2 = 0.5$ A	-0.29	-34
Magnetized CT	4.66	-273
Demagnetization by $R_2 = 2\ \Omega$	1.18	-82
Demagnetization by $R_2 = 12\ \Omega$	-0.3	-47

errors on the measured currents. The principle of the experiments basically relies on the use of a differential structure implementing a CT under test (denoted CT) as well as a reference CT (denoted CN) with very high accuracy. In the experimental setup only CT may be submitted to a dc magnetization of its core. Therefore, an auxiliary winding featuring 50 turns and fed by a dc current is used. To demagnetize CT, its secondary winding features a PWM switched resistor of equivalent value in series with a resistance R_N. The ac current to measure feeds both the primary windings of CT and CN. The secondary windings of CT and CN (which are wound in opposite directions) feed R_N with opposite currents of similar intensity and the voltage V_N at the ends of R_N is proportional to the difference between these two currents. The CV amplitude and phase error is therefore determined from the measurement (performed by lock-in amplifier of the voltage drop of V_N. More detailed description of the method used for CT error measurement and test bed can be found in [13]. The layout of the demagnetization device is shown in Fig. 3.

According to [13], the ratio error of measured current amplitude can be calculated as real part of the voltage ΔV measured by a lock-in amplifier as

$$\varepsilon_I = \frac{\mathrm{Re}(\Delta I)}{I_N} = \frac{\mathrm{Re}(\Delta V)}{R_N} \cdot \frac{R_{\mathrm{ref}}}{V_{\mathrm{ref}}} \cdot 100(\%). \tag{4}$$

The error of measured current phase can be obtained from imaginary part of voltage as

$$\delta_I = \frac{\mathrm{Im}(\Delta I)}{I_N} = \frac{\mathrm{Im}(\Delta V)}{R_N} \cdot \frac{R_{\mathrm{ref}}}{V_{\mathrm{ref}}} \cdot (\mathrm{rad}) \tag{5}$$

where V_{ref} is a voltage measured across the R_{ref}.

The measurement results are summarized in Table I.

The measurements were performed at two CT operation points: 1) the CT was measuring at 20% of its nominal current I_N and 2) at 10% of I_N. This corresponds to state of non-loaded network. First, the ratio error and phase displacement in initial state were measured. Then, the CT was magnetized by dc current pulse of 10 A into the auxiliary winding of 50 turns and the errors were measured again. After that the demagnetization by PWM switched resistor was performed and the CT errors were measured once more. Both methods of demagnetization by increased input current and by PWM switched resistor were used. The results in Table I show that for 10% of the nominal current I_N the value of $R_2 = 2\ \Omega$ was not enough to fully CT demagnetization. The R_2 have to be increased.

Waveforms taken during the measurement are shown in Figs. 5–8. Upper trace (a) represents control signal for the transistors (u_g), second trace (b) is the CT secondary current (i), third trace (c) is the CT flux (Ψ_2) calculated as an integral of the CT secondary voltage, and bottom trace (d) is the voltage across the resistor $R_2(u_{R2})$. The waveforms show that

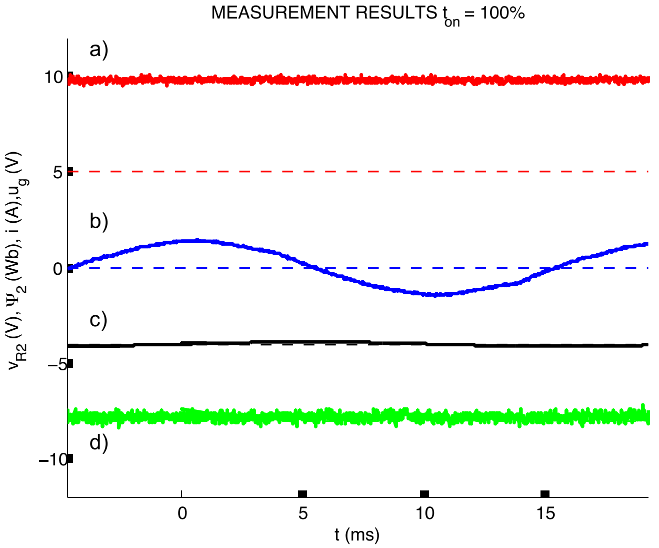

Fig. 5. Waveforms for $t_{\mathrm{ON}} = 100\%$. (a) Control signal for the transistor. (b) Secondary current of CT. (c) CT flux (d) Secondary voltage of CT.

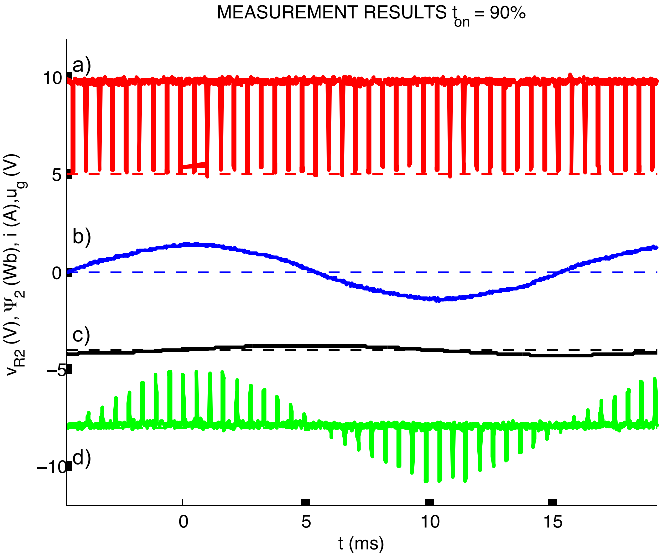

Fig. 6. Waveforms for $t_{\mathrm{ON}} = 90\%$. (a) Control signal for the transistor. (b) Secondary current of CT. (c) CT flux (d) Secondary voltage of CT.

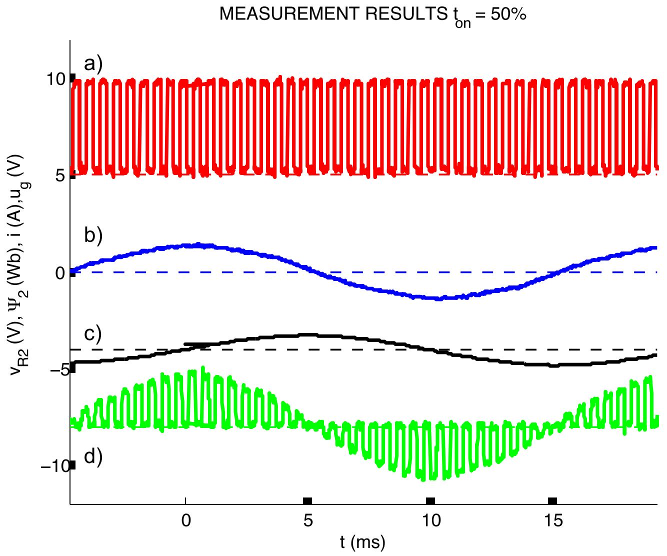

Fig. 7. Waveforms for $t_{ON} = 50\%$. (a) Control signal for the transistor. (b) Secondary current of CT. (c) CT flux (d) Secondary voltage of CT.

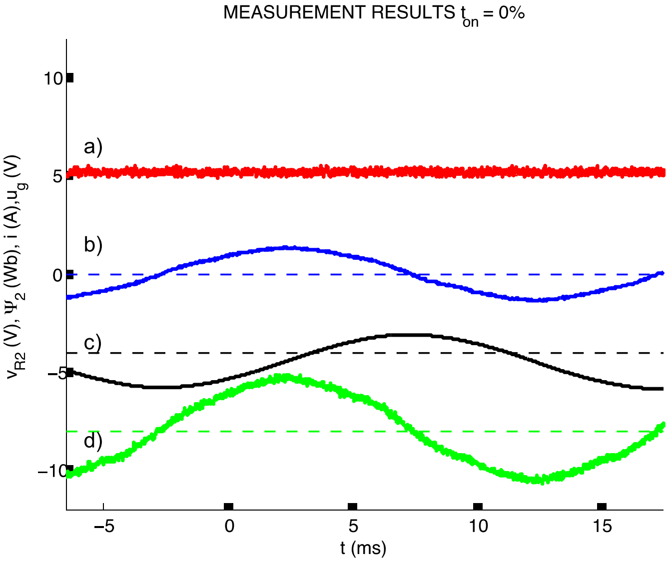

Fig. 8. Waveforms for $t_{ON} = 0\%$. (a) Control signal for the transistor. (b) Secondary current of CT. (c) CT flux (d) Secondary voltage of CT.

switching frequency of the PWM was selected sufficiently high so that the CT flux is very close to sinewave, no distortion is visible.

V. CONCLUSION

The dc magnetization has great influence on the CT accuracy, therefore demagnetization of CT is needed especially for high-accuracy CTs used for the energy meters. One way to demagnetize the CT is to increase the input current and thus saturate the core, however, this method is not possible in real application when CT is connected to the supply network. That is why the second method based on momentary increase of the load of the CT was tested. This can be done either by the resistor network or by PWM switching of a single resistor.

The main advantage of the PWM switched resistor is that compared with resistor network it enables possibility to use one resistor in the whole range of current and the value of increased load is controlled just by the means of PWM that allows continuous control of the load.

We have demonstrated that using this method it is possible to restore heavily magnetized 0.2% accuracy class CT back to its nominal error without removing it from the network.

During a practical use in an electrical network, the PWM switched resistor should be actuated to demagnetize the core typically in 15 min intervals and every time after the detected transient. The demagnetization phase should last about 10 s, because of magnetic viscosity of the core material.

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