TRANSIENTS IN NO-LOAD CONDITION OF POWER TRANSFORMER 20/0,4 kV

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Innovative approach in power system transient analysis is presented in the paper, applying a new proposed method to process data obtained from processor built in modern protection power relays. The transients, described here appeared precisely while turning the power transformer on and setting it in the no-load condition. The analyzed power transformers 20/0,4 kV are installed to meet the auxiliary needs of the transformer substation TS 110/20 kV Osijek-4 with electric power. Time response graphic presentations of main power parameters and Fourier analysis of higher harmonics are presented in this paper.

Key words: Fourier analysis, harmonics, no-load condition, phase current, phase voltage

Prijelazne pojave u praznom hodu energetskog transformatora 20/0,4 kV

Ovaj rad predstavlja inovativan pristup u analizu prijelaznih pojava u elektroenergetskom sustavu korištenjem novopredloženih načina obrade podataka dobivenih iz procesora ugrađenog u moderne zaštitne releje u elektroenergetskom sustavu. Prijelazne pojave se precizno registriraju tijekom uključivanja energetskog transformatora i puštanja u prazni hod. Analizirani su energetski transformatori 20/0,4 kV u TS 110/20 kV Osijek-4 koji služe za opskrbu električnom energijom vlastitih potreba transformatorske stanice. U radu su grafički prikazani vremenski odzivi glavnih električnih parametara kao i Fourierova analiza viših harmonika.

Ključne riječi: fazni napon, fazna struja, Fourierova analiza, harmonici, prazni hod

1
Introduction
Uvod

The power transients in the low and middle voltage network have been in the researcher's focus for a long time. Dynamic time response of electric waveforms depends on changes of impedance along the power system, impulsive changes of load or nonlinear customer's or system's devices. The power transient analyzed and measured in the paper typically appears while turning the power transformer on and setting it in the no-load condition. The analyzed power transformers 20/0,4 kV have been installed to meet the auxiliary needs of the transformer substation TS 110/20 kV Osijek-4 with electric power. The mathematical tool used here to describe the physical phenomenon has been developed within the program package for the analysis of events in distribution network, which is named TOP (The Output Processor). Here, detailed parameters of two installed power transformers are: 3TBNv 250-24x/K, rated voltage 20/0,4 kV, secondary winding Dyn5, rated power Sn=250 kVA. The primary intention of the measurement procedure was the monitoring of the power transformer function and the comparison of the transformer's parameters and dynamic responses during the above described process. Power transformers examination procedure started on 10 March 2009 and lasted two months, including the research period.

All the measured and memorized values of the three phase voltages and three phase currents have been obtained from the protection relay REF54x. Such device is shown in Fig. 1. Sampling speed of measurement points is 2 kHz which means 2000 samples per second. All the values have been analyzed by the above mentioned program package TOP and also illustrated in the next several figures. After that, Fourier analysis of higher harmonics for the current of the first phase follows and the results are graphically presented.

Figure 1 *Protection relay REF54x*
Slika 1. *Zaštitni relej REF54x*

2
Currents forms and values during turning on the power transformer without connected load
Oblici i vrijednosti struja prilikom uključenja energetskog transformatora bez opterećenja

Only in the case of single-phase transformer the transients could be avoided by controlling the moment of turning on the power transformer when voltage waveform comes up to actual core magnetic flux. In the model of three phase power transformer, the transients of the phase's inrush currents are unavoidable.

A high asymmetry of the magnetic flux occurs in the ferromagnetic material of the transformer's iron core at the moment of the powering up of the device. It is caused by the well-known hysteresis phenomenon process. The magnitude of the initial current of no-load condition of power transformer depends on the momentary value of

phase voltages and residual magnetism (direction and magnitude) of the power transformer core. Inrush current magnitude decreases in the case of booted voltage around its maximum value. On the other hand, residual magnetism depends on the load characteristics (power factor and load magnitude) at the moment the power transformer is turned off and also depends on the core material of the power transformer. If the power transformer is connected to sinusoidal voltage source, magnetic flux is also sinusoidal and the transformer core is magnetized by spiky (non sinusoidal) current. As a direct consequence, a significant distortion of the magnetizing current waveform appears followed by enormous values of inrush currents (6-8 times the rated current) and significant contribution of the DC component in the moment of connection.

Certain time transformer core becomes saturated, and the current magnitude of the no-load condition of power transformer becomes restricted by air core reaction. Existence of the primary delta winding causes the need that all of the three phases be treated as independently connected to power system. After the power transformer has been switched on, the worst case of insulation strain is when only one phase has a large initial current value and the other two phases values nullify each other (equal values and opposite directions).

All three measured phase current's waveforms are presented in Fig. 2.

The significant change of current values of all three phases is caused by different momentary voltage value of all three phases at the moment of turning on of the power transformer and by residual magnetism. The difference in the initial phase current values is visible during time period from 100 ms to 500 ms in Fig. 3. Here, time interval duration of transient process is approximately 400 ms. The described process could last for several seconds in a real power system, depending on the vicinity of the power source. Series resistance of transmission and distribution power line reduces the initial value of current and shortens the time interval of the oscillations (attenuation effect). Power transformers (small units) connected far away from power sources usually have shorter duration of no-load condition transients.

Current values I1, I2, I3, oscillate from the maximum value 100 A to 10 A, and after the transient period the values decrease to the stationary value of magnetization current (1 A). The measured current waveforms present the magnetization process of power transformer core. To clarify, current waveforms in Fig. 3 have been derived from Fig. 2 within determined time interval from 0 to 200 ms.
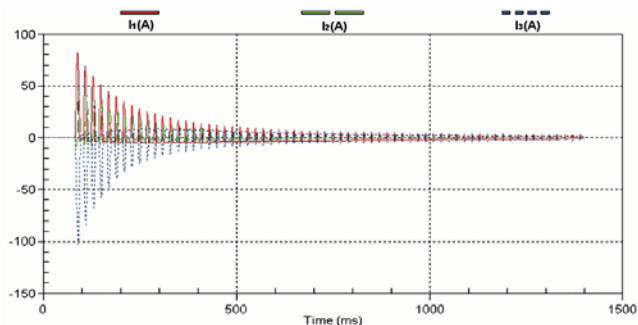

Figure 2 *Current waveforms of all three phases I1, I2, I3 after turning on the power transformer in no-load condition*
Slika 2. *Valni oblici struja sve tri faze I1, I2, I3 nakon uključenja energetskog transformatora u prazni hod*
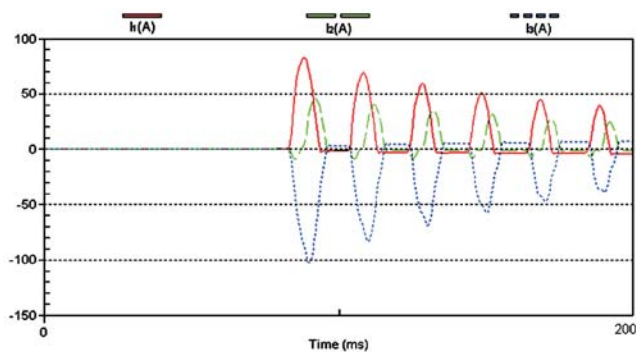

Figure 3 *Interval detailed review of current waveforms of all three phases I1, I2, I3 after turning on the power transformer in no-load condition*
Slika 3. *Intervalni detaljni prikaz valnih oblika struja sve tri faze I1, I2, I3 nakon uključenja energetskog transformatora u prazni hod*

All three current waveforms and values presented in Fig. 3. differ from each other in the values depending on the moment of the turning the device on, but each of the waveforms is characterized by only one half-cycle of sinusoidal wave (predominant second harmonic component). Flux density inside iron core of power transformer is below saturation value which causes neglecting values of inrush current in half of a period.

It is very important to emphasize that the value of phase I3 is the highest in comparison with other phase currents. In fact, the value of the phase current is the highest for the phase which the momentary voltage value passes near the zero value at the moment of connection to distribution network.

According to measuring data obtained from examination procedure after the production of the transformer unit, during the no-load condition with rated voltage and frequency, measured values of the phase's currents (after transient period) are: I1= 1,39 A, I2= 0,99 A, I3= 1,33 A. The measured phase current values and corresponding waveforms as time-dependent after the connection of transformer to the network are presented in Figures 4-6.
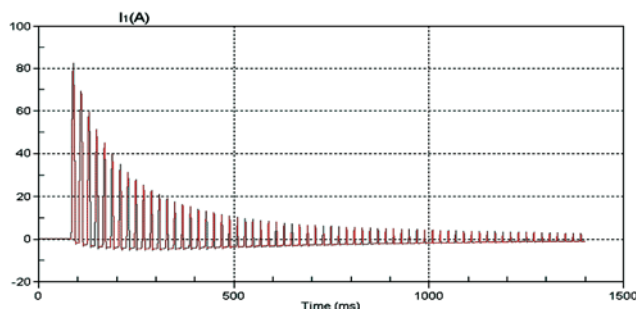

Figure 4 *Current values of the first phase I1 after power transformer connection (no-load condition) to power network*
Slika 4. *Vrijednosti struje prve faze I1 nakon uključenja energetskog transformatora na elektroenergetsku mrežu (prazni hod)*

3
Fourier analysis
Fourierova analiza

Power transformer generates higher harmonic currents (CH) during its function due to its non-linear nature. Harmonic spectrum also depends on the load which is connected to secondary windings of power transformer. The usual values of higher harmonics are: the 3rd CH from 0,3 to 0,5 of the first current harmonic (1st CH), the 5th CH is
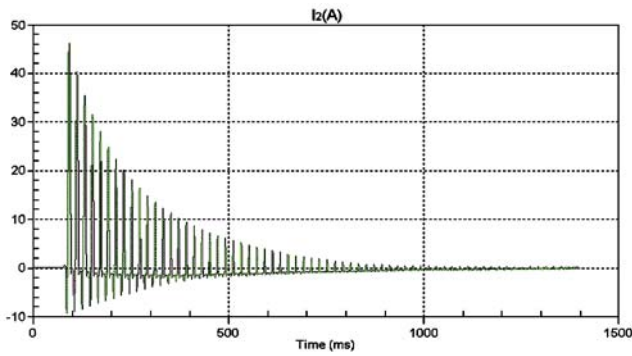
Figure 5 *Current values of the second phase I2 after power transformer connection (no-load condition) to power network*
Slika 5. *Vrijednosti struje druge faze I2 nakon uključenja energetskog transformatora na elektroenergetsku mrežu (prazni hod)*
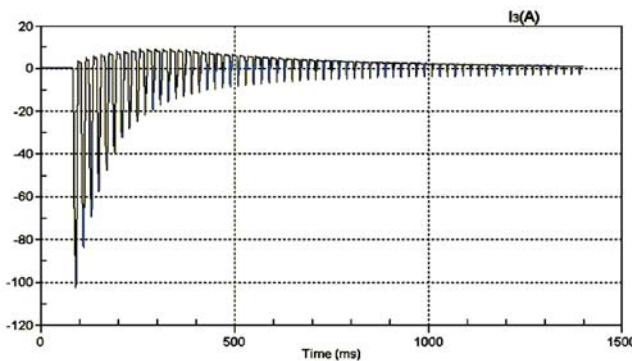

Figure 6 *Current values of the third phase I3 after power transformer connection (no-load condition) to power network*
Slika 6. *Vrijednosti struje treće faze I3 nakon uključenja energetskog transformatora na elektroenergetsku mrežu (prazni hod)*

between 0,1 and 0,3 of the 1st CH and the 7th CH is about 0,04 to 0,1 of the 1st CH. Higher current harmonics than the 7th CH are of negligible value. Higher harmonic currents cause additional power losses and reduce power transformer capabilities.

Herein, the second harmonic is emphasized, which occurs exceptionally in the case of no-load condition of power transformer [4]. For a better understanding of momentary values and waveforms of phase voltages and currents obtained during power transients in network, it is recommended to apply Fourier analysis. It is used to present the measured waveform, equations (1) and (2) broken down into its components – contribution of DC component, basic harmonic (f=50 Hz) and higher harmonics, equations (3). The existence of the asymmetrical second current harmonic of inrush current at the moment of switching power transformer (no-load condition) on the network makes it possible to apply the numeric power protection relays to restrain from action.

$$f(t) = f(t \pm nT) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left(a_n \cos(n\omega t) + b_n \sin(n\omega t) \right) \quad (1)$$

relevant to:

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} c_n \sin(n\omega t + \varphi_n), \quad (2)$$

where pertinent factors are:

$$c_n = \sqrt{a_n^2 + b_n^2},$$

$$\varphi_n = \operatorname{arctg}\left(\frac{a_n}{b_n} \right),$$

n - ordinal number of harmonic ($n = 1,2,3, …,\infty$)

$\omega = \dfrac{2\pi}{T}$ - circular frequency of the first harmonic

T - time period of periodic function

Coefficients of Fourier analysis are counted by the following relations:

$$\frac{a_0}{2} = \frac{1}{T} \int_0^1 f(t)\,dt,$$

$$a_n = \frac{2}{T} \int_0^T f(t) \cos(n\omega t)\,dt, \quad (3)$$

$$b_n = \frac{2}{T} \int_0^T f(t) \sin(n\omega t)\,dt.$$

Factor $a_0/2$ represents the mean value of periodic function, and coefficients a_n i b_n are amplitudes of n-th harmonic (n=1,2,3, …,∞).

After description of mathematical model of Fourier analysis, it is further on applied to the measured power transients.

All three phase current transient waveforms I1, I2, I3 after turning on the power transformer (no-load condition) are processed by Fourier analysis to get basic and higher harmonics contribution in initial waveform.
As an example, Fourier analysis of measured transient current of the first phase (shown above in Fig. 4) has been made and the result is presented in Fig. 7.
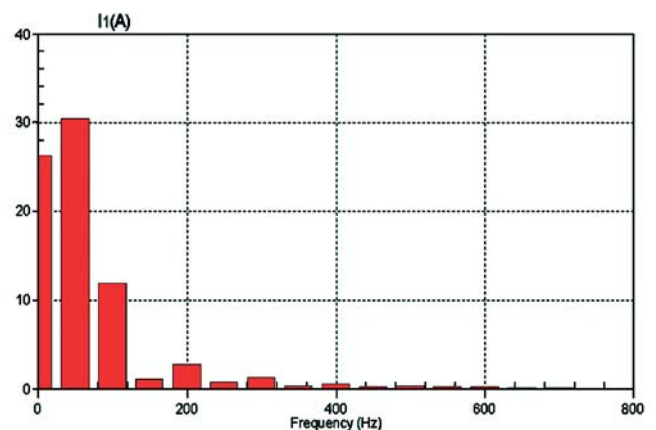

Figure 7 *Contributions of basic and higher current harmonics in measured waveform after Fourier analysis of the phase I1*
Slika 7. *Udjeli osnovnog i viših harmonika u mjerenom valnom obliku struje prve faze I1 nakon Fourierove analize*

The basic harmonic with frequency 50 Hz has the highest value as expected. DC current has the second importance of influence on contribution in initial waveform. The second harmonic with frequency 100 Hz has also great impact on the initial current waveform.

Having analyzed the contribution of other harmonics, it is easy to notice that only the fourth harmonic (200 Hz) has an important influence unlike all the others which have almost negligible influence. Waveforms of the first six
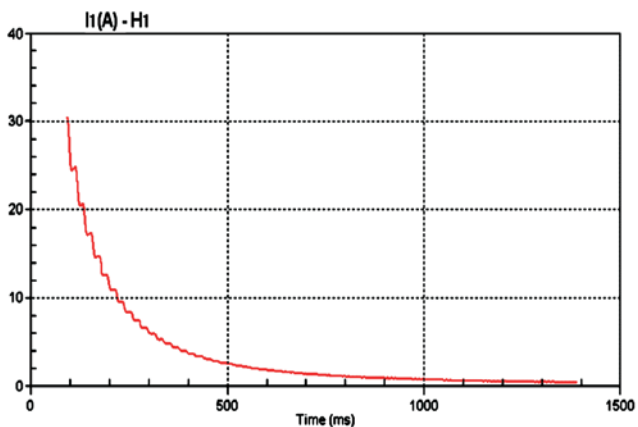
Figure 8 *The first current harmonic waveform of the first phase I1 after Fourier analysis*
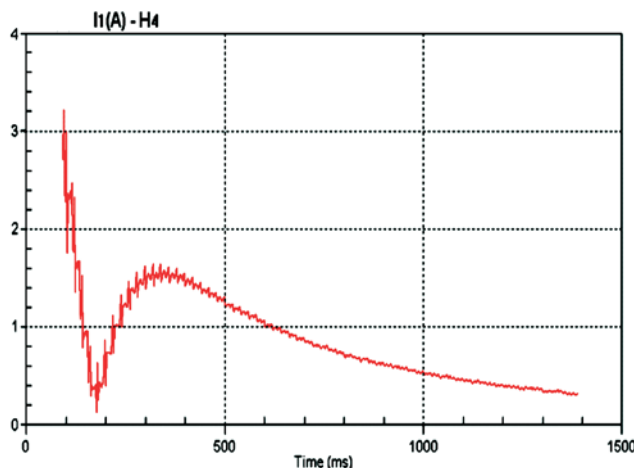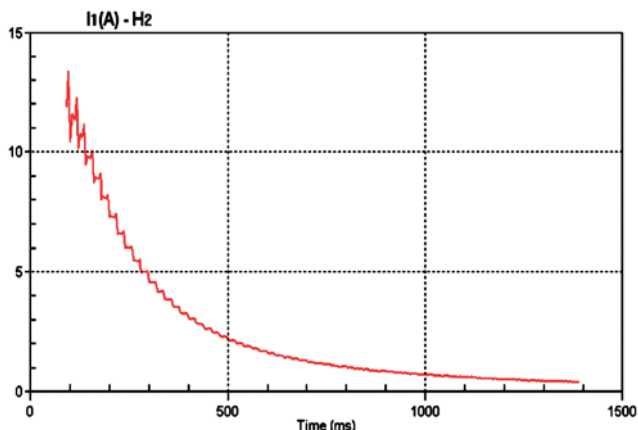**Slika 8.** *Valni oblik prvog harmonika struje prve faze I1 nakon Fourierove analize*

Figure 9 *The second current harmonic waveform of the first phase I1 after Fourier analysis*
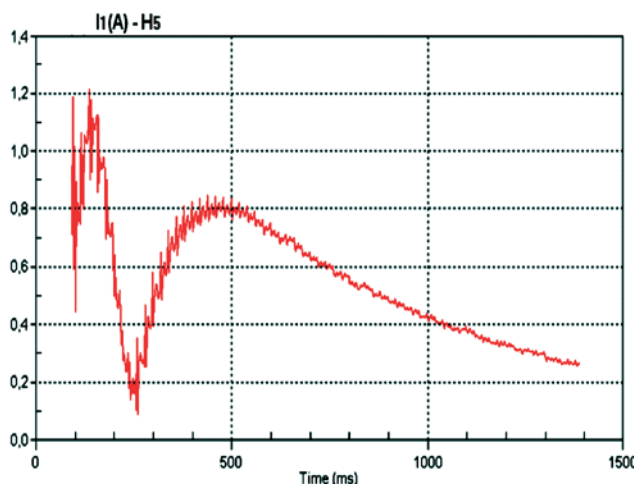**Slika 9.** *Valni oblik drugog harmonika struje prve faze I1 nakon Fourierove analize*

Figure 10 *The third current harmonic waveform of the first phase I1 after Fourier analysis*
Slika 10. *Valni oblik trećeg harmonika struje prve faze I1 nakon Fourierove analize*

Figure 11 *The fourth current harmonic waveform of the first phase I1 after Fourier analysis*
Slika 11. *Valni oblik četvrtog harmonika struje prve faze I1 nakon Fourierove analize*

Figure 12 *The fifth current harmonic of the first phase I1 after Fourier analysis*
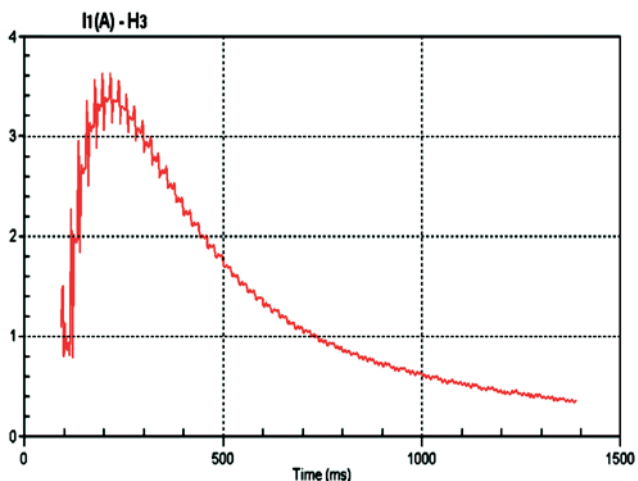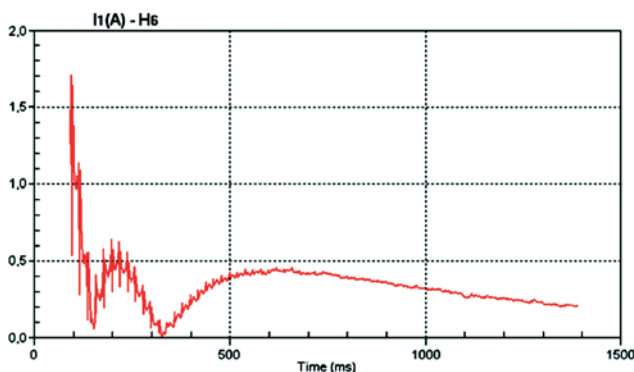**Slika 12.** *Valni oblik petog harmonika struje prve faze I1 nakon Fourierove analize*

Figure 13 *The sixth current harmonic waveform of the first phase I1 after Fourier analysis*
Slika 13. *Valni oblik šestog harmonika struje prve faze I1 nakon Fourierove analize*

harmonics are presented in Figures 8-13.

All presented waveforms of higher harmonics (from the second to the sixth harmonics) have dominantly high inrush currents inside the time period from 0 to approximately 500 ms, which points out magnetization process of transformer core. Also, it is noticeable that current initial values for all three phases, so called inrush values are up to 100 A.

All existing higher harmonics following with their values have been obtained by the Fourier analyses. It is also easy to see significant contribution of DC component of the current.

All current harmonics as well as phase currents of transformer have extremely high values at the moment of connection of transformer on distribution network and after the transient period (500 ms) intensely decrease to the minimum value.

It is significant to notice that the decreasing current values inside the transient period are a common parameter of all presented waveforms (the first harmonic, DC component and other higher harmonics), although the second and the fifth harmonic in the starting moment have the inverse (increasing) trend. So, the process of magnetization of the core of the power transformer is presented here by all pertinent components of current waveform.

4
Conclusion
Zaključak

All measured values of the transient process of turning on the power transformer 20/0,4 kV in the no-load condition have been given by new numeric protection relay. After the measuring procedure, data were analyzed by the program TOP, The Output Processor. All three electric phases' currents waveforms are precisely presented with their maximum values and are explained. After that, Fourier analysis for the first current phase is made.

The new developed approach to numeric protection relay which is usually used only for safety purpose of primary equipment makes it possible to dispose of precisely measured data of very high density dot pitching. The measured data, given from numeric relays are processed by the program package TOP, The Output Processor. The high quality of all real measured data analyses has been achieved as well as all higher harmonics contribution in transient waveforms obtained by the application of Fourier analyses.

5
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