Research on Transformer Interaction Caused by Inrush Current and Parametric Study of This Phenomenon

P. Heretík, M. Kováč, M. Smitková, A. Beláň, V. Volčko and P. Heretík

Abstract—The phenomenon of sympathetic interaction between transformers is discussed in this paper. The phenomenon of sympathetic interaction between transformers, which is very likely to occur when a transformer is energised on to a system where are other transformers already connected, changes significantly the duration and the magnitude of the transient magnetising currents in the transformers involved and in the line supplying transformers. At the same time, its characteristics are further analyzed by numerical simulation in Matlab-Simulink Program. The sympathetic inrush current could influence the transformer differential protection and even cause mal-operation differential protection of switching and already energized transformer.
Based on simplified equivalent circuit of two shunt-wound transformers, the magnetic analytical expression and rule of bias magnetic attenuation are analyzed. After that, the reasons of sympathetic inrush current generation are illustrated. The effects parameters of supplying system and transformers, such as load, system resistance, manners of connections of windings and manners of transformer grounding to sympathetic inrush current are then analyzed deeply by analytical analysis. The conclusion is validated by using emulate program.

Keywords—Network resistance, Simulation of transient phenomena, Sympathetic inrush current, Transformer connections.

This work was supported by the agency VEGA MŠVVaŠ SR under Grant No. 1/1045/11´Integrated Analysis of the Renewable Energy Sources´.

P. Heretík is with the Department of Electrotechnics and Applied Energetics, Faculty of electrical engineering and Information Technology, Slovak University of Technology, Bratislava, SK 81219 Slovak Republic (e-mail: Pavol.Heretik@stuba.sk).

M. Kováč is with the Department of Electrotechnics and Applied Energetics, Faculty of electrical engineering and Information Technology, Slovak University of Technology, Bratislava, SK 81219 Slovak Republic (e-mail: Matus.Kovac@stuba.sk).

M. Smitkova was with the Faculty of Mathematics Physics and Informatics, Comenius University in Bratislava. Now is with the Department of Electrotechnics and Applied Energetics, Faculty of electrical engineering and Information Technology, Slovak University of Technology, Bratislava, SK 81219 Slovak Republic (e-mail: Miroslava.Smitkova@stuba.sk).

A. Beláň is head of the Department of Electrotechnics and Applied Energetics, Faculty of electrical engineering and Information Technology, Slovak University of Technology, Bratislava, SK 81219 Slovak Republic (e-mail: Anton.Belank@stuba.sk).

V. Volčko is with the Department of Electrotechnics and Applied Energetics, Faculty of electrical engineering and Information Technology, Slovak University of Technology, Bratislava, SK 81219 Slovak Republic (e-mail: Vladimir.Volcko@stuba.sk).

P. Heretík is with the Department of Electrotechnics and Applied Energetics, Faculty of electrical engineering and Information Technology, Slovak University of Technology, SK 81219 Slovak Republic (e-mail: Peter.Heretik@stuba.sk).

I. Introduction

MAGNETIZING inrush current occurs during the energization of a single transformer connected to a power system network with no other transformers. However, the energization of a transformer connected to a network in the presence of other transformers, as shown in Fig. 1, which are already in operation, leads to the phenomenon of sympathetic inrush current.

Although, severity of the inrush current is higher during single transformer energization, the sympathetic inrush current is of special importance due to its unusual characteristics. The inrush current in a transformer decays, usually, within a few cycles, but the sympathetic inrush current persists in the network for a relatively longer duration.

In recent years, there are several reports of closing a transformer without load which led to the mal-operation of the adjacent transformer differential protection or generator differential protection.

The reason is that when we close a transformer without load it will produce excitation current which passes the system resistance causes asymmetrical fluctuation of the busbar voltage, resulting in saturations generating sympathetic inrush current in adjacent transformer.

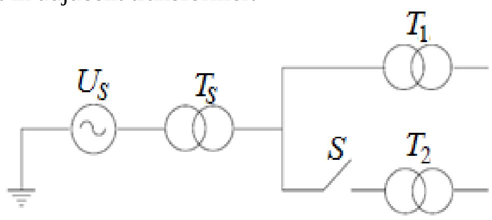

Fig. 1 Sympathetic interaction between transformers

The available literature includes numerous investigations on the inrush current phenomenon in power transformers and its impact on the design and operation of protection schemes [2–5]. Most of the approaches are based on the electrical equivalent circuit [5, 7, 8] or magnetic equivalent circuit [10–12]. Most of them expound partial analysis of the influencing factors of sympathetic inrush current, but not comprehensive.

In this work, in order to solve the problems brought by the sympathetic inrush current, we expound mathematical theory of sympathetic inrush current of two shunt wound transformer and we also focus on some special factors influencing sympathetic inrush current (load of tertiary transformer winding, impact of transformers connection and manner of transformer grounding) which understanding is very meaningful in an effort to avoid mal-operation of differential and generator protections.

Therefore, this paper will analyze various factors of network affecting transient phenomena theoretically, based on the predecessors analysis of sympathetic inrush current generation mechanism, and through MATLAB simulation test. We also hope to provide a certain reference for understanding it and solving the impact brought by it.

II. Process of Sympathetic Inrush Between Parallel Transformers

Utilizing the coupled electromagnetic model proposed in [10], simulation was carried out in [15] and [16] to illustrate the process of sympathetic inrush interaction between the two parallel connected transformers. In that case T1 and T2 are two identical 230/69 kV, 15 MVA single-phase transformers (referring to Figure 1). The simulated currents i_1, i_2 and i_s are displayed in Figure 2-4, respectively.

As it can be seen, the inrush current i_2 reached maximum peak right after the energisation of T2 and then decayed gradually, while the sympathetic inrush current i_1 built up in T1 gradually reached its maximum peak and then gradually decayed; the supply current i_s is the sum of the currents i_1 and i_2, the peaks of sympathetic inrush current i_1 and of the inrush current i_2 occur in direction opposite to each other, on alternate half cycles.

Waveforms of these currents will be analyzed in detail in the following sections.

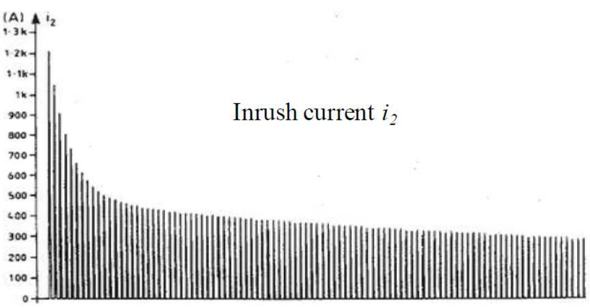

Fig. 2 Current in transformer T2 [15]

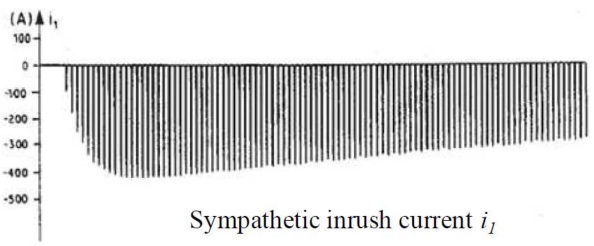

Fig. 3 Current in transformer T1 [15]

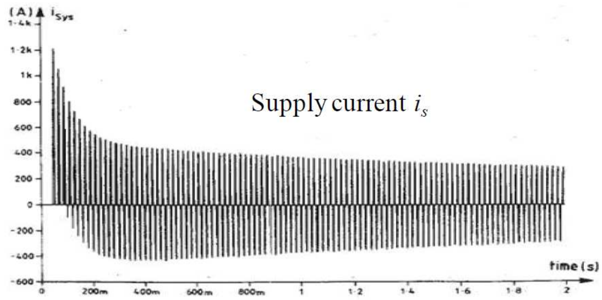

Fig. 4 Current in the electrical source [15]

III. Analytical Analysis of Sympathetic Inrush Current

A. *Decaying Mechanism of Inrush Current in case of single transformer*

For studying the origin mechanism of the sympathetic interaction, at first the inrush current of only a single-phase energized transformer is analyzed from the point of magnetic flux. The equivalent circuit is shown in fig.5.

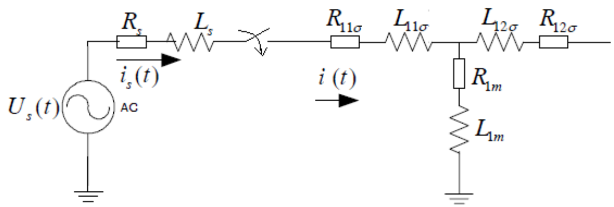

Fig. 5 The equivalent circuit of a single-phase energized transformer

When a single-phase unloaded transformer is energized with the source, the circuit's voltage equation and flux equation can be expressed as follow [26]:

$$u_s(t) = \left(R_s + R_1\right) i_1 + \frac{d\psi}{dt} \tag{1}$$

where:

$$\psi = \left(L_s + L_\sigma + L_m\right) i = Li \tag{2}$$

R_s and L_s is the system resistance and inductance respectively, R_1 and L_σ is the transformer leakage resistance and inductance and L_m is the magnetic inductance which is a nonlinear inductance and chosen as average inductance of the magnetic circuit, Ψ the total winding magnetic flux.

Integrating equation (1) in a cycle gives:

$$\int_t^{t+\Delta t} u_s(t)dt = \int_t^{t+\Delta t} \left[\left(R_s + R_1\right) i_1\right] dt + \Delta\psi \tag{3}$$

The electromotive force of source is symmetrical sine wave, so the left of equation (3) is equal to zero. Thus the total flux change per cycle can be expressed as follow:

$$\Delta\psi = -\int_t^{t+\Delta t} \left[\left(R_s + R_1\right) i_1\right] dt \tag{4}$$

Equation (4) expresses that the decaying quantity of the total winding flux is associated with the system resistance and the transformer leakage resistance. Generally the inrush current has plentiful DC component, so the winding's flux decays for the influence of resistance, and with the resistance increased, the flux decays faster [27].

B. Mechanism Analysis of sympathetic interaction between transformers in parallel

For the comprehensive analysis of the various influencing factors of sympathetic inrush current, it is necessary to understand the physical nature of it. This section will be on the basis of the previous section and Literatures [6, 9], which simply introduces the formation process of sympathetic inrush current through the flux analytical expression and bias flux attenuation between two parallel operation transformers lay a theoretical basis for the analysis of various influencing factors.

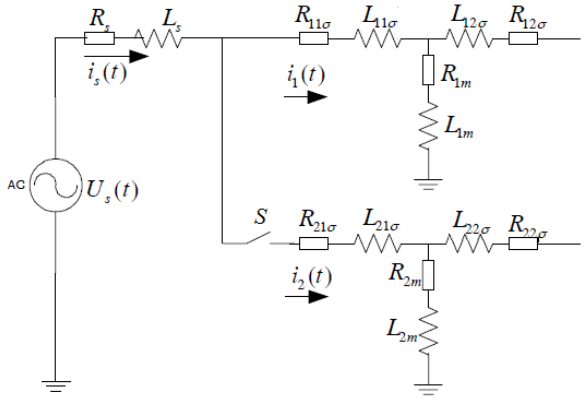

Fig. 6 Equivalent circuit used to analyze sympathetic inrush for transformers in parallel according to Fig. 1

Operating one transformer, and closing the other without loads, generally, has two connection modes: parallel or series. In this work we will focus on parallel connection which is shown in Fig. 6.

In the Fig. 6 $U_s(t)$ is the system source voltage; R_S & L_s are respective resistance and inductance of electrical system, $R_{11\sigma}$ & $L_{11\sigma}$, $R_{12\sigma}$ & $L_{12\sigma}$, R_{1m} & L_{1m}, are respective resistance and leakage inductance of transformer T1's primary and secondary winding and also the excitation resistance and excitation inductance; $R_{21\sigma}$ & $L_{21\sigma}$, $R_{22\sigma}$ & $L_{22\sigma}$, R_{2m} & L_{2m}, are respective resistance and inductance of transformer T2 similarly to the transformer T1.

Next we will consider $i_1(t)$, $i_2(t)$ are respective inrush current of operation T1 and the closing transformer T2 without load. Causing $R_1 = R_{11\sigma} + R_{1m}$, $L_1 = L_{11\sigma} + L_{1m}$, $R_2 = R_{21\sigma} + R_{2m}$, $L_2 = L_{21\sigma} + L_{2m}$. Supposed that the system voltage source is $u_s(t) = U_m \sin(\omega t+\alpha)$, and α is represented the close angle.

The application of the circuit principle we can write:

$$\begin{aligned} & R_s i_s + L_s \frac{di_s}{dt} + R_1 i_1 + \frac{d\psi_1}{dt} = U_m \sin(\omega t + \alpha) \\ & R_1 i_1 + \frac{d\psi_1}{dt} = R_2 i_2 + \frac{d\psi_2}{dt} \\ & i_s = i_1 + i_2 \end{aligned} \quad (5)$$

Where ψ_1 and ψ_2 are respective fluxes of transformers T1 and T2. Obviously, the relation (5) is a nonlinear equation. In order to analyse the flux relation of the two transformers, we should get analytical formula because we need to do linear process with relation (5). Here, the non-linear excitation inductance L_{1m} and L_{2m} are replaced by the average inductance of the transformer magnetizing circuit and we will further consider the same transformers: $L_1 = L_2 = L$， $R_{1m} = R_{2m} = R$.

Then using Laplace transform and Laplace inverse transform, we can get two transformers flux expression [6, 9, 13]:

$$\begin{aligned} \psi_1(t) = & \frac{L}{Z} U_m \sin(\omega t + \alpha - \varphi) - \frac{1}{2}[\psi_1(0) - \\ & -\psi_2(0)] e^{-\frac{R+2R_s}{L+2L_s} t} + \frac{1}{2}\left[\psi_1(0) - \psi_2(0)\right] e^{-\frac{R}{L} t} \end{aligned} \quad (6)$$

$$\begin{aligned} \psi_2(t) = & \frac{L}{Z} U_m \sin(\omega t + \alpha - \varphi) - \frac{1}{2}[\psi_1(0) - \\ & -\psi_2(0)] e^{-\frac{R+2R_s}{L+2L_s} t} - \frac{1}{2}\left[\psi_1(0) - \psi_2(0)\right] e^{-\frac{R}{L} t} \end{aligned} \quad (7)$$

Where:

$$Z = \sqrt{(R + 2R_s)^2 + (L + 2L_s)^2}$$

$$\varphi = \arctan \frac{\omega (L + 2L_s)}{R + 2R_s}$$

And ψ_1 (0) and ψ_2 (0) are the respective initial fluxes of transformers T1 and T2.

From equations (6) and (7), it can be seen that both ψ_1 and ψ_2 consist of one sinusoidal component and two exponential DC components. The AC component and the first DC component are the same, but the second DC component in ψ_1 is opposite to that in ψ_2, therefore i_1 and i_2 are opposite to each other and appear alternately.

Also, because the both DC components in ψ_2 are negative, so the maximum peak of i_2 would appear right after the energisation of T2, whilst the DC components in ψ_1 are of opposite polarity and the time constant of the first DC component $\tau_1 = (L + 2L_s)/(R + 2R_s)$ is smaller than that of the second DC component $\tau_2 = L/R$, so i_1 will gradually reach the maximum peak, and gradually decay afterwards as we could see in fig. 7.

The simplified analytical analysis shows in a general way the variation of flux-linkages in T1 and T2 which depends on the time constants formed by the inductances and resistances of the circuit branches. In real situation, the core inductance is nonlinear and therefore the time constants cannot be so readily determined. So this is the reason for using simulation methods described in the next chapter. [18-21]

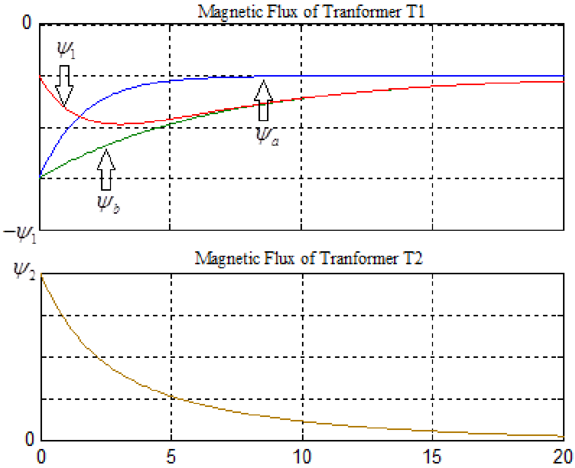

Fig. 7 Waveforms of magnetic fluxes of transformers T1 and T2

Note: For aperiodic components of magnetic fluxes ψ_1 and ψ_2 in the previous figure, we could apply:

$$\psi_a(t)=\frac{1}{2}\left[\psi_1(0)+\psi_2(0)\right]e^{-\frac{R+2R_s}{L+2L_s}t}$$
$$\psi_b(t)=\frac{1}{2}\left[\psi_1(0)+\psi_2(0)\right]e^{-\frac{R}{L}t} \quad (8)$$

Summing the individual magnetic fluxes (ψ_1, ψ_2) we get relation for total magnetic flux:

$$\psi(t)=\frac{2L}{Z}U_m\sin(\omega t+\alpha-\varphi)-[\psi_1(0)$$
$$-\psi_2(0)]e^{-\frac{R+2R_s}{L+2L_s}t} \quad (9)$$

Considering linear characteristic of transformers T1 and T2 ($i_1=\psi_1/L_1, i_2=\psi_2/L_2$) we could write equation represented line current (i_s) based on relation (9):

$$i_s(t)=\frac{2}{Z}U_m\sin(\omega t+\alpha-\varphi)-\frac{1}{L}[\psi_1(0)$$
$$-\psi_2(0)]e^{-\frac{R+2R_s}{L+2L_s}t} \quad (10)$$

Now is apparent that, one of two transient component from (6,7) with time constant $\tau_2=L/R$ is circulating around the loop formed by the two transformer windings in series without flowing in the transmission line during the sympathetic phenomenon (Fig. 8), whilst the second one with time constant $\tau_1=(L+2L_s)/(R+2R_s)$ is created by system voltage source.

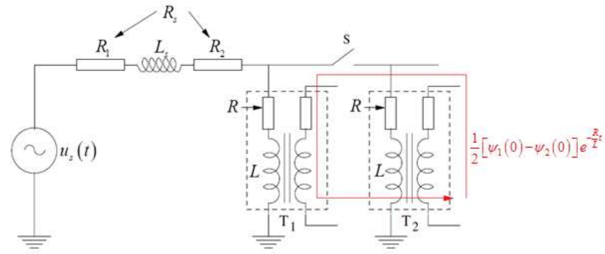

Fig. 8 Transient magnetic component of magnetic flux which represents circulating current

It is interesting to note that the circulating current, both with respect to magnitude and rate of decay, is entirely independent of the characteristics of the transmission line circuit, being determined solely by the inductance and resistance of the transformers themselves in conjunction with the initial bus voltage, the frequency, and the switching angle.

C. Decaying Mechanism of Sympathetic Inrush Current in case of two identical transformers

In [17, 15] and [14], the interactions between parallel transformers were analysed using the voltage drop across circuit resistances, with system and transformer winding inductances neglected, which is summarized as follows (by referring to Figure 6).

Before closing S, only the magnetizing current of the unloaded transformer T1 flows through the system; application of kirchhoff's law we could write:

$$u_s(t)=(R_s+R_1)i_1+\frac{d\psi_1}{dt} \quad (11)$$

The integration of u_s over one cycle gives:

$$\int_t^{t+\Delta t}u_s(t)dt=\int_t^{t+\Delta t}\left[(R_s+R_1)i_1\right]dt+\Delta\psi_1 \quad (12)$$

Where Δt is of one cycle interval and $\Delta\psi_1$ represents the flux change per cycle in transformer T1.

Considering the system source $u_s(t)$ is symmetric periodical function, so:

$$\int_t^{t+T}U_m\sin(\omega t+\alpha)dt=0 \quad (13)$$

We could write the following relation for the flux change per cycle in transformer T1:

$$\Delta\psi_1=-\int_t^{t+\Delta t}\left[(R_s+R_1)i_1\right]dt \quad (14)$$

According to previous equation if current of transformer i_1 is symmetrical and transformer T2 is not connected, $\Delta\psi_1$ will be zero. This situation corresponds to the state before switching transformer T2.

After closing S, saturation of transformer T2 causes a transient inrush current i_2 which flows through R_s. Due to the unidirectional characteristic of the inrush current, each cycle transformer T1 experiences an offset flux by an amount of:

$$\Delta\psi_1 = -\int_t^{t+\Delta t} \left[\left(R_s + R_1 \right) i_1 + R_s i_2 \right] dt \qquad (15)$$

Meanwhile, an offset flux per cycle $\Delta\psi_2$ is produced in transformer T2 by:

$$\Delta\psi_2 = -\int_t^{t+\Delta t} \left[\left(R_s + R_2 \right) i_2 + R_s i_1 \right] dt \qquad (16)$$

At the initial stage, both $\Delta\psi_1$ and $\Delta\psi_2$ are of the same polarity and mainly depend on the voltage drop caused by the inrush current i_2. The accumulation of $\Delta\psi_1$ drives transformer T1 into saturation, while the effect of $\Delta\psi_2$ is to reduce the initial offset flux in transformer T2 so as to produce the decay of inrush current i_2.

As the transformer T1 becomes more and more saturated, a sympathetic inrush current i_1 gradually increases from the steady state magnetizing current to a considerable magnitude. Noted that as the transformer T1 saturates with the polarity opposite to that of transformer T2, the peaks of the sympathetic inrush current i_1 are with polarity opposite to that of inrush current i_2, on alternate half cycles. As a result, the voltage asymmetry on transformer terminals caused by the inrush current i_2 during one half cycle is reduced by the voltage drop produced by the sympathetic inrush current i_1 during the subsequent half cycle. This decreases both $\Delta\psi_1$ and $\Delta\psi_2$, and therefore reduces the changing rate of the magnitude of both the increasing sympathetic inrush current i_1 and the decaying inrush current i_2.

After a certain time, the increase of i_1 and decay of i_2 can reach a point that:

$$\left(R_s + R_1 \right) i_1 = -R_s i_2 \qquad (17)$$

At this point, the flux change per cycle $\Delta\psi_1$ is zero and hence current i_1 stops increasing. Thereafter, the polarity of $\Delta\psi_1$ reverses and starts to reduce the offset flux in the transformer T1, as a result, the sympathetic inrush current i_1 begins to decay (so does the inrush current i_2). Since both decaying currents have the same amplitude but with polarities opposite to each other, no voltage asymmetry is produced on the transformer terminals and the flux change per cycle in each transformer only depends on the winding resistance of each transformer.

This is one of the reasons for the inrush current to be significantly prolonged in power systems with large transformers energised, as the winding resistances of these transformers are normally of relatively small value.

Note: The fluxes ψ_1, ψ_2 attenuate respectively by the value of (15)(16) periodically and the damping role of the system resistance disappears, and it is attenuating, in accordance with the basic time constant τ_1 and τ_2 which results in longer attenuation.

$$\tau_1 = L_1 / R_1 \qquad (18)$$

$$\tau_2 = L_2 / R_2 \qquad (19)$$

IV. Establishment of System Simulation Model

In order to study effect of the special system factors on sympathetic inrush current, we will establish system simulation platform according to Fig. 9. This platform is based on Matlab-Simulink program and it uses three phase transformer unit, which enable us further study of influence of various transformer connection and grounding connection.

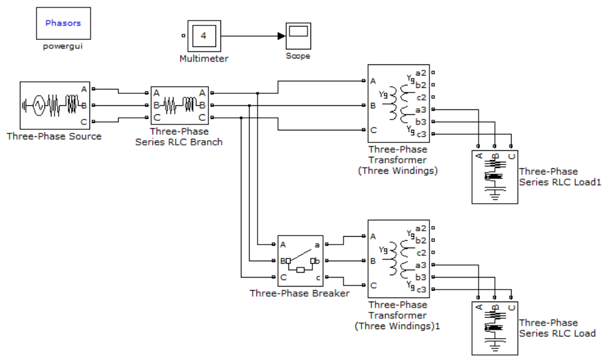

Fig. 9 Simulation platform of the model in Matlab-Simulink program

In Fig. 9, the rated voltage U_s is 500kV, the rated frequency is 60Hz. The two transformers are exactly the same, having same parameters: the rated power is 150MVA, the rated voltage are (500, 230, 35) kV, the primary, the secondary and tertiary winding resistance are 0.002(pu), the leakage inductance are 0.08(pu), the excitation resistance are 500(pu), the basic magnetization curve using two broken line linearization processing, two broken line determined by three of points (0,0;0.0024,1.2;1.0,1.52).

V. Parametric Study of Impact Selected System Factors on Sympathetic Inrush

Sympathetic interaction between two identical single-phase transformers (rated at 150 MVA, 500/230/35 kV) in Matlab Simulink program. [16]. The schematic diagram of the circuit used in modeling tests is the same with that shown in Figure 6.

In the tests, circuit breaker was set to close at the positive-going zero crossing of the applied voltage and the residual flux of the transformer (both in terms of polarity and magnitude) was fixed by feeding a direct current through the winding before each test for a short period.

We will consider initial state: Connection Yg-yg-yg, no load on the tertiary winding. The simulation result is expressed in Fig. 10. (System current, sympathetic inrush current in transformer T1 and inrush current in transformer T2)

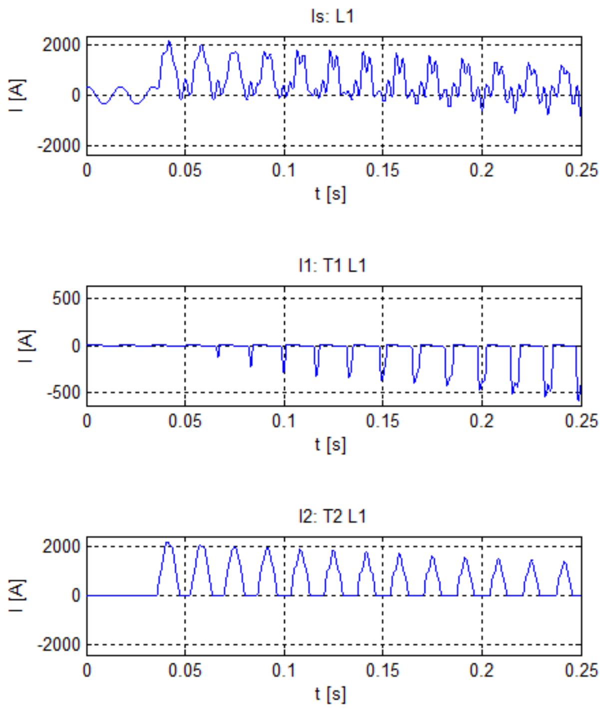

Fig. 10 Sympathetic inrush currents of parallel transformers modeled according to Fig. 9.

Note: In the model we assume: Rs = 6.55Ω, Ls = 0.36H, T1 initial flux is given by time of switching transformer T2, T2 initial flux $\psi_2(0) = 0$.

In this section, when we study the impact factors of inrush current we'll take corresponding situation in Fig. 10 as reference. So that we can compare the effect of the various factors directly.

The effects such as line and transformer loop circuit resistance, load of tertiary transformer winding, manners of grounding neutral point and effect of transformer connection will be investigated in detail.

A. *Impact of Line Resistance*

In previous analytical analysis we found out that inrush current is produced by the existence of R_s. Clearly, the greater the value of R_s is and the greater flux will change weekly, and accordingly it is benefit for the production of inrush current.

In contrast, the smaller R_s is, the less obvious the relationship is, which is bad for the production of inrush current. Specially, when R_s =0 Ω, (15, 16), so the voltage drop will not appear and at this moment, inrush current phenomenon will disappear.

In Fig. 11 there are the current waveforms of current (i_s) according to R_s after being increased to 10, 20 and 30Ω. Line resistance is a key factor in determining the magnitude of the sympathetic inrush current in the transformer already connected. Increase of line resistance generates higher maximum peak of sympathetic inrush current and accelerates the build-up to reach the maximum peak as we could see in Fig. 11:

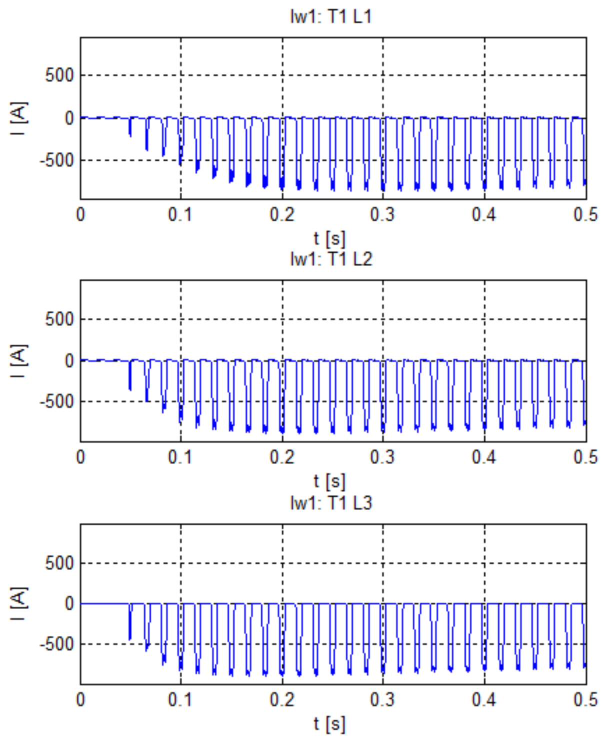

Fig. 11 Sympathetic inrush Current of transformer T1 (R_s = 10, 20 and 30Ω)

B. *Impact of the Transformer Loop Circuit Resistance*

When the transformer is switched on, there are usually some power devices between it and the parallel transformer. These devices have a certain resistance and negligible inductance.

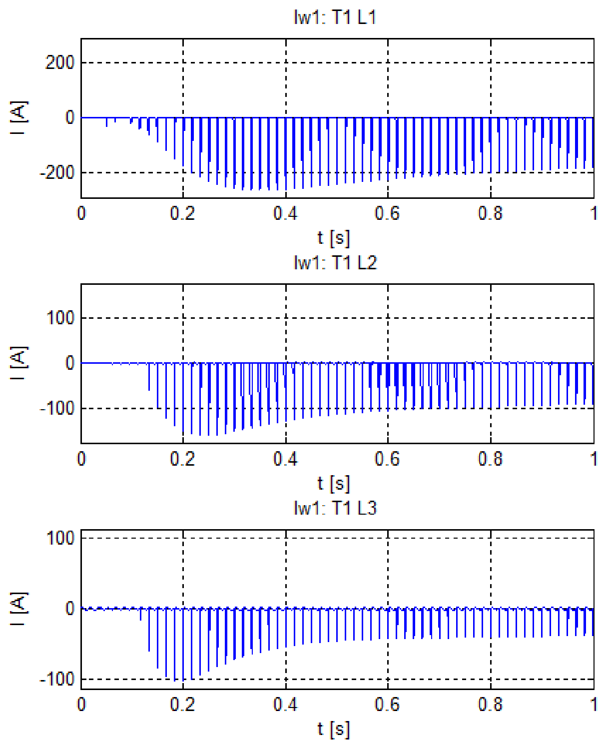

Fig. 12 Sympathetic inrush Current of transformer T1 (R_{loop} = 18, 35 and 50Ω)

The simulation result in Fig. 12 displays inrush current of T1 according to rising resistance between transformers (loop circuit resistance):

Resistance of the transformer loop circuit according to Fig. 12 rapidly reduces the magnitude of sympathetic inrush current of already connected transformer and speeds up the decay of the sympathetic interaction (this represents the case of two parallel transformers separated by transmission lines of long length instead of a short electrical connection).

C. Impact of Load of Tertiary Transformer Winding

When the transformer is switched on to a heavy load, the peak values of both types of load (active or inductive reactive) cause that sympathetic inrush current of the already energized transformer is considerably smaller compared to the unload case (Fig. 13) but inrush current of the switching transformer remains nearly unchanged.

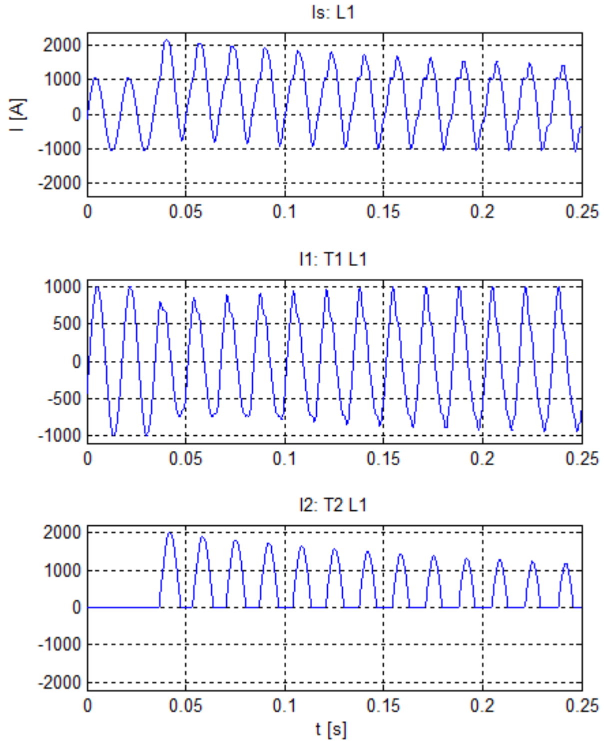

Fig. 13 Impact of active load of tertiary winding on sympathetic inrush phenomena (P = 5MW)

Note: In the model we assume load of both transformers by active power P = 5MW (Fig. 13) or inductive reactive load Q=5MVAr (Fig. 14).

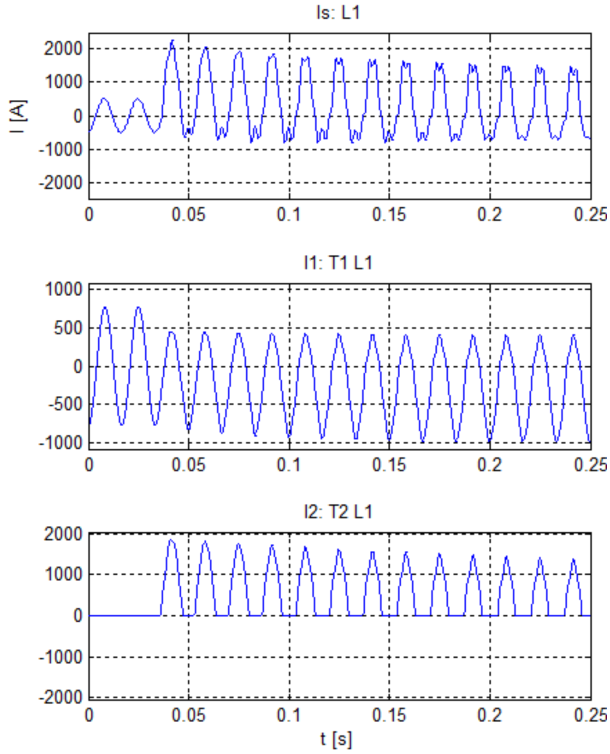

Fig. 14 Impact of inductive reactive load of tertiary winding on sympathetic inrush phenomena (P = 5MVAr)

D. Effect of Manners of Grounding Neutral Point of Transformer Windings

Comparing the inrush current waveform of different grounding ways is in Fig. 15. (Only system current is shown).

The inrush current is the greatest and the speed of attenuation is the slowest when it is directly grounded system. When transformers are grounded through resistance or inductance speed and amplitude is the second. While it is not grounding, the speed is slow and the amplitude is minimum.

The reason of this behavior is that grounding system produces a zero-sequence current, which should make the inrush current increase.

However, closing transformer without load under any grounding methods will enable the adjacent transformer to produce inrush current, and the difference between them is not obvious. Thus when we close a transformer without load, break the neutral grounding switch which cannot eliminate inrush current, but it can only reduce inrush current to a very small extent.

Note: In the model we assume same grounding method for both transformers.

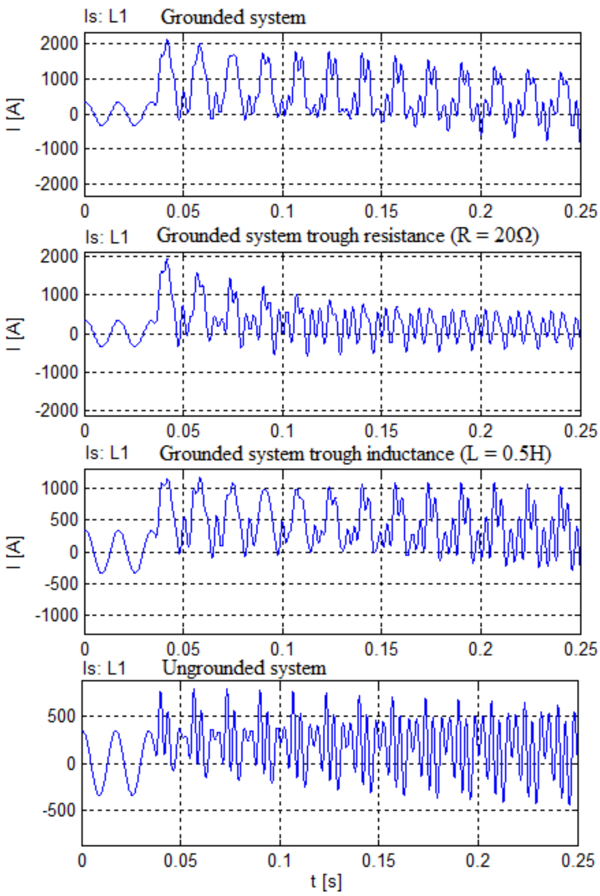

Fig. 15 Effect of various manners of transformers grounding on sympathetic inrush current phenomenon

E. Effect of Transformers Connection

Analysis of different ways of transformer connection to system inrush current is shown in Fig. 16.

The inrush current is the greatest and the speed of attenuation is the slowest when both winding of transformer are connected to triangle (Dd). The inrush phenomenon is the least and the speed of attenuation is the fastest when one winding of transformer is connected in one way and second another (Yd). And when both winding of transformer are connected to star (Yy) speed and amplitude is nearly similar to first case.

The differences between various size of amplitude and speed of attenuation are not obvious but as well as in the previous case transformer without load in every connection will enable the adjacent transformer to produce inrush current.

Note: In the model we assume same connection of both transformers.

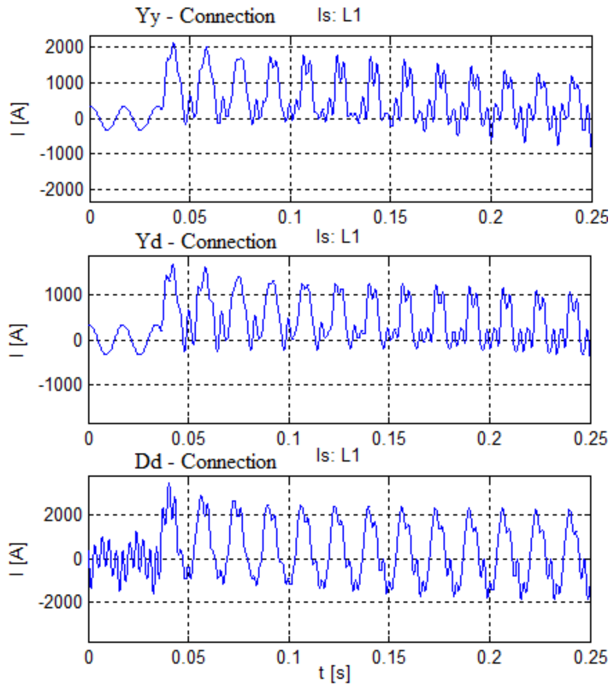

Fig. 16 Effect of various transformer connection on sympathetic inrush current phenomenon

VI. CONCLUSION

In this paper, we have presented a detailed formulation and modeling for the analysis of sympathetic inrush phenomenon for the configuration of parallel and series connected transformers. Two 125MVA, three-phase, 500/230/35 kV, transformers are modeled using MATLAB/Simulink/ SimPowerSystems. Simulink equations of the transformers are then solved simultaneously with the circuit equations of the power system network. The analysis is done on three-phase units. Subsequently, three-phase simulation results are also reported.

It is well known that the sympathetic inrush current persists in the network for a much longer duration than the inrush current for the singly connected transformer. The special parameters affecting the magnitude and duration of the current, such as impact of system and loop resistance, load of tertiary winding, grounding manners and ways of transformer winding connection are modeled and discussed in detail. It is observed that even though an increase in the load of tertiary winding decreases the magnitude of the sympathetic inrush current appreciably, there is little effect on its duration. The change in various manners of grounding and different types of winding connection can cause significant variations in the phenomenon of the sympathetic inrush currents.

When the sympathetic interaction between transformers happens, the operating transformer coud be saturated and generate the sympathetic inrush, which could influence transformer differential protection and therefore the exact understanding of this phenomenon is very important.

ACKNOWLEDGMENT

This work was supported by the agency VEGA MŠVVaŠ SR under Grant No. 1/1045/11´Integrated Analysis of the Renewable Energy Sources´.

REFERENCES

[1] S. V. Kulkarni, "Influence of system operating conditions on magnetizing inrush phenomenon of transformer," *International Conference on transformers, TRAFOTECH-94, Bangalore, India*, pp. VI 19–23, January 1994.

[2] R. Yacamini and A. A. Nasser, "Calculation of inrush current in single-phase transformers," *IEE Proceedings - Electric Power Applications*, vol. 128, no. 6, pp. 327– 334, November 1981.

[3] R. Yacamini and A. Abu-Nasser, "Numerical calculation of inrush current in single-phase transformers," *IEE Proceedings - Electric Power Applications*, vol. 128, no. 6, pp. 327–334, 1981.

[4] C. Paul, Y. Ling, and A. Basak, "Investigation of magnetizing inrush current in a single-phase transformer," *IEEE Transactions on Magnetics*, vol. 24, no. 6, pp. 3217– 3222, November 1988.

[5] C. E. Lin, C. L. Cheng, C. L. Huang, and J. C. Yeh, "Investigation of magnetizing inrush current in transformers, Part I - numerical simulation," *IEEE Transactions on Power Delivery*, vol. 8, no. 1, pp. 246–254, January 1993.

[6] Y. Wang, X. Yin, D. You, and T. Xu, "Analysis on the influencing factors of transformer sympathetic inrush current," in Proc. IEEE Power Energy Soc. Gen. Meeting—Conversion and Delivery of Electrical Energy in the 21st Century, Jul. 2008, pp. 1–8.

[7] G. Baoming, A. T. de Almeida, Z. Qionglin, and W. Xiangheng, "An equivalent instantaneous inductance-based technique for discrimination between inrush current and internal faults in power transformers," *IEEE Transactions on Power Delivery*, vol. 20, no. 4, pp. 2473–2482, October 2005.

[8] A. A. Adly, H. H. Hanafy, and S. E. Abu-Shady, "Utilizing preisach models of hysteresis in the computation of three-phase transformer inrush currents," *Electric Power Systems Research*, vol. 65, pp. 233–238, 2003.

[9] W. Gong, J. Liu, and X. He, "Research on transformer syspathetic inrush current in initail period of power system", in Proc. Electricity Distribution (CICED), 2012 China International Conference, Sept. 2012, pp. 1–5.

[10] R. Yacamini and H. S. Bronzeado, "Transformer inrush calculation using a coupled electromagnetic model," *IEE Procedings - Science, Measurement and Technology*, vol. 141, no. 6, pp. 491–498, November 1994.

[11] M. Elleuch and M. Poloujadoff, "A contribution to the modeling of three phase transformers using reluctances," *IEEE Transactions on Magnetics*, vol. 32, no. 2, pp. 335– 343, March 1996.

[12] K. S. Smith, L. Ran, and B. Leyman, "Analysis of transformer inrush transients in offshore electrical systems," *IEE Proceedings - Generation, Transmission and Distribution*, vol. 146, pp. 89–95, January 1999.

[13] Bi Daqiang, Wang Xiangheng, Li Dejia, et al. *Theory Analysis of the Sympathetic Inrush in Operating Transformers*. Automation of Electric Power Systems, 2005,29(6):1-8.

[14] J. Peng, "Assessment of Transformer Energisation Transients and Their Impacts on Power Systems", Phd. Thesis, Manchester 2013.

[15] H. S. Bronzeado, P. B. Brogan, and R. Yacamini, "Harmonic analysis of transient currents during sympathetic interaction," IEEE Transactions on Power Systems, vol. 11, no. 4, pp. 2051-2056, 1996.

[16] P. Heretík, M. Kováč, M. Smitková, A. Beláň and V. Volčko , "Analysis of Selected System Factors on Sympathetic Inrush Current of Shunt Wound Transformers," Wseas *Proceedings - Electric Power and Energy Systems*, pp. 333–337, 2013.

[17] H. Bronzeado and R. Yacamini, "Phenomenon of sympathetic interaction between transformers caused by inrush transients," IEE Proceedings - Science, Measurement and Technology, vol. 142, no. 4, pp. 323-329, 1995.

[18] S. Schramm, C. Sihler, and S. Rosado, "Limiting sympathetic interaction between transformers caused by inrush transients," in International Conference on Power Systems Transients (IPST), Delft, the Netherlands, 2011.

[19] M. M. Saied, "A study on the inrush current phenomena in transformer substations," in 36th IEEE Industry Applications Conference, pp. 1180-1187,Chicago, USA, Sep. 2001.

[20] I. Hassan, H. V. Nguyen, and R. Jamison, "Analysis of energizing a large transformer from a limited capacity engine generator," in IEEE Power Engineering Society Winter Meeting, pp. 446-451, Singapore, Jan. 2000.

[21] M. R. Iravani, A. K. S. Chandhary, W. J. Giesbrecht, I. E. Hassan, A. J. F. Keri, K. C. Lee, J. A. Martinez, A. S. Morched, B. A. Mork, M. Parniani, A. Sarshar, D. Shirmohammadi, R. A. Walling, and D. A. Woodford, "Modelling and analysis guidelines for slow transients. II. Controller interactions; harmonic interactions," IEEE Transactions on Power Delivery, vol. 11, no. 3, pp. 1672-1677, 1996.

[22] I. Sadeghkhani, A. Mortazavian, N. Haratian, A. Ketabi, and R. Feuillet: "Artificial Intelligence Techniques to Evaluate Transformer Switching Overvoltages," International Journal of Energy, Issue 1, Vol. 6, 2012.

[23] Marius-Constantin Popescu, Nikos Mastorakis, Gheorghe Manolea, Aida Bulucea, Liliana Perescu-Popescu,"Thermal Model Parameters Transformers", WSEAS Transactions on Power Systems, Issue 6, Volume 4, pp. 199-209 June 2009.

[24] N. K. Dhote, J. B. Helonde," Diagnosis of Power Transformer Faults based on Five Fuzzy Ratio Method", WSEAS Transactions on Power Systems, Issue 3, Volume 7, pp. 114-125, July 2012.

[25] M. Srinivasan, A. Krishnan,"Effects of Environmental Factors in Transformer's Insulation Life", WSEAS Transactions on Power Systems, Issue 1, Volume 8, pp. 35-44, January 2013.

[26] Shi Shiwen. Large-scale generator transformer set protection [M], Beijing Hydraulic and Electric Power Press, 1987.

[27] D. Shao, X. Yin, Z. Zhang, D. Chen, and K. Zhang," Research on Sympathetic Interaction between Transformers", Universities Power Engineering Conference, 2007. UPEC 2007. 42nd International 2007, Sept 2007. 273-276.

Pavol Heretík (MSc.) was born in Trnava in 1989, Slovakia. He received the MSc. degree in power engineering from the Faculty of Electrical Engineering and Information Technology of Slovak University of Technology, Bratislava, in 2012. At present he works as a Phd. Sdudent at the Department of Power Engineering, FEI SUT in Bratislava. His teaching and research activities are in the area of transient phenomena in power system and power system protection. He is a member of some grants and scientific projects in area of power engineering. He is author or coauthor of approximately 20 papers at conferences and in journals.

Matúš Kováč (MSc.) was born in Trnava in 1988, Slovakia. He received the MSc. degree in power engineering from the Faculty of Electrical Engineering and Information Technology of Slovak University of Technology, Bratislava, in 2012. At present he works as an Phd. Sdudent at the Department of Power Engineering, FEI SUT in Bratislava. His teaching and research activities are in the area of transient phenomena in power system and power system stability. He is a member of some grants and scientific projects in area of power engineering. He is author or coauthor of approximately 15 papers at conferences and in journals.

Miroslava Smitková (MSc. PhD.) was born in Bratislava in 1977. In 2001, she graduated from the Faculty of Mathematics, Physics and Informatics of the Comenius University in Bratislava. In 2009, she received her PhD in the field of Electrical Power Engineering at the Department of Electrical Power Engineering at the Faculty of Electrical Engineering and Informatics of SUT in Bratislava. Her scientific activities are focused on the topic of renewable energy sources and hydrogen production. Her publishing activities include 4 lecture books, 2 articles in expert periodicals, 47 articles in proceedings from international and domestic conferences, 35 articles in periodicals and 12 articles in popular periodicals.

Anton Beláň (assoc. prof., MSc. PhD.) was born in Bojnice in 1970. He graduated from the Slovak University of Technology, Faculty of Electrical Engineering and Information Technology in 1993. In 2002 he successfully accomplished his PhD. study. At present he a Head of the Department of Power Engineering, FEI SUT in Bratislava. His teaching and research

activities are in the area of protection relays, control of electrical power systems and power quality. He presented the results of his work as author or co-author of approximately 80 publications (2 books, 4 university textbooks, 74 papers in journals and at international conferences).

Vladimír Volčko (MSc.) was born in Levoča in 1988, Slovakia. He received the MSc. degree in power engineering from the Faculty of Electrical Engineering and Information Technology of Slovak University of Technology, Bratislava, in 2012. At present he works as an Phd. Sdudent at the Department of Power Engineering, FEI SUT in Bratislava. His teaching and research activities are in the area of transient phenomena in power system and Smart Meter-Grid systems. He is a member of some grants and scientific projects in area of power engineering. He is author or coauthor of approximately 20 papers at conferences and in journals.

Peter Heretík (Msc.) was born in Trnava, Slovakia, in 1987. He received the Master degree in nuclear power engineering at the Slovak University of Technology, Bratislava in 2011. Currently, he is studying the PhD. study at Slovak University of Technology in Bratislava. His interests include electrical systems planning, electrical calculations and analysis.