EMC OF ELECTRICAL SYSTEMS – GALVANIC COUPLING

(PART I.)

*Irena KOVÁČOVÁ, *Ján KAŇUCH, **Dobroslav KOVÁČ
*Department of Electrical Drives and Mechatronics, Technical University of Košice, Letná 9, 042 00 Košice
**Department of Theoretical Electrical Engineering and Electrical Measurement, Park Komenského 3,
042 00 Košice, Slovak Republic
Tel: +421-55-6022273; Fax: +421-55-6330115
E-mail: Irena.Kovacova@tuke.sk, E-mail: Jan.Kanuch@tuke.sk, E-mail: Dobroslav.Kovac@tuke.sk

SUMMARY

This papers deals with the analysis of the electromagnetic compatibility (EMC) – galvanic coupling problems focused to the area of power electrical systems. Description of galvanic coupling problem is divided into two separate parts according the length of common conductors or the working frequency. First part (PART I.) is dealing with the galvanic coupling problem of concentrated parameter circuits, it means such that the length of common conductors is short or processed signals have low working frequency. The second one (PART II.) is analyzing the same problem for circuits with distributed parameters, it means such that the length of common conductors is long or processed signals have high working frequency. For detail problem investigation a mathematical analysis, computer simulation method and verification measuring are used, too.

Keywords: *electromagnetic compatibility, galvanic coupling, common conductors, long lines*

1. INTRODUCTION

Problem of galvanic coupling is dealing with individual electric equipment or their parts interconnections by such a way, that exists minimum one or (in some cases as for example feeding net) more common conductors, which are interconnected these equipments and so the mutual influencing is generated.

2. SOLUTION FOR LOW FREQUENCIES AND CONCENTRATED PARAMETERS

The working frequencies and common conductor lengths must be taken always into account. In all cases of the galvanic coupling the fact that electrical components are not ideal and so they are containing certain parasitic capacitances, inductances and real resistances is valid. In due to higher working frequency of currents flowed by the common conductors they must be taken as circuits with distributed parameters during the process of predictive result galvanic coupling investigation. If the working frequencies will be lower, then the interconnecting circuits can be taken as circuits with concentrated parameters.

2.1. One common conductor - theoretical analysis

Minimum two or more electric circuits, which are mutually galvanically interconnected by one common conductor with its length *l*, represent such type of galvanic coupling. In due to low frequency operation the common conductor electrical parameters is possible to define by concentrated parameters of its resistance *R* and inductance *L*. If we will suppose in the next step, that the conductor will be made by cooper, so the voltage drop on its resistance *R* will be much smaller in comparison with voltage drop across its inductance *L*, which is caused by time depending change of current. So, for analyzed problem simplifying the conductor resistance will be neglected in following. Schematic representation of the described problem is shown in following figure Fig. 1.

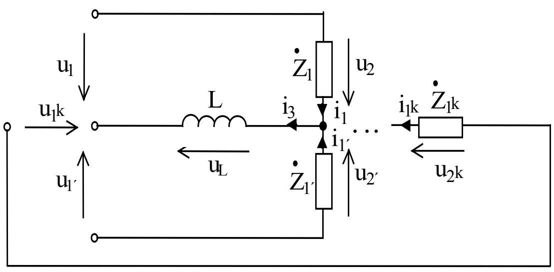

Fig. 1 Schematic representation of circuit interconnections by one common conductor

Mathematical description of situation in investigated circuit is then given by next system of integral-differential equations,

$$u_1 - u_L - u_2 = u_1 - L.\frac{di_3}{dt} - \left(R_1.i_1 + L_1.\frac{di_1}{dt} + \frac{1}{C_1}.\int i_1.dt \right) = 0$$

$$u_{1'} - u_L - u_{2'} = u_{1'} - L.\frac{di_3}{dt} - \left(R_{1'}.i_{1'} + L_{1'}.\frac{di_{1'}}{dt} + \frac{1}{C_{1'}}.\int i_{1'}.dt \right) = 0$$

$$u_{1^k} - u_L - u_{2^k} = u_{1^k} - L.\frac{di_3}{dt} - \left(R_{1^k}.i_{1^k} + L_{1^k}.\frac{di_{1^k}}{dt} + \frac{1}{C_{1^k}}.\int i_{1^k}.dt \right) = 0$$

$$i_3 = i_1 + i_{1'} + \sum_{k=''}^{n} i_{1^k} \qquad (1)$$

where (n+2) is number of all different loops, which contains the same common conductor. In the case of great number of loops the analytic investigation of galvanic coupling influence on individual electric circuits is relatively complicated, so the available computer numerical simulation programs is possible to utilize.

In following step we will try to obtain imagination about mutual circuits interaction amount, caused by galvanic coupling existence. The investigation will be done for only two interacting circuits. For analytic investigation simplifying is suitable to suppose, that pure resistors create the loads in the both galvanic connected circuits and that the circuits are in steady states and supplied from DC voltage source as it is shown in figure Fig. 2.

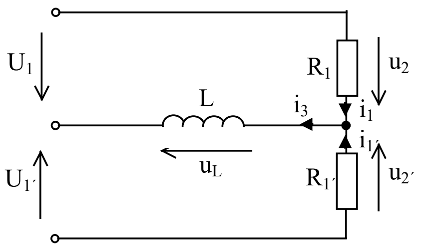

Fig. 2 Investigated circuit

For circuit steady state will be valid the next equations.

$$U_1 - u_L - u_2 = U_1 - L.\frac{di_3}{dt} - R_1.i_1 = U_1 - R_1.i_1 = 0 \quad (2)$$

$$U_{1'} - u_L - u_{2'} = U_{1'} - L.\frac{di_3}{dt} - R_{1'}.i_{1'} = U_{1'} - R_{1'}.i_{1'} = 0 \quad (3)$$

$$i_3 = i_1 + i_{1'} \quad (4)$$

Let the jump change of supplying voltage from value $U_{1'}$ to zero will be supposed in lower circuit and none change of supplying voltage or load in the upper circuit. The time dependence description of voltage u_2 can be obtained by the next differential equation system solving.

$$U_1 - L.\frac{di_3}{dt} - R_1.i_1 = 0 \quad (5)$$

$$-L.\frac{di_3}{dt} - R_{1'}.i_{1'} = 0 \quad (6)$$

$$i_3 = i_1 + i_{1'} \quad (7)$$

By its transformation to the Laplace – Carson's domain the next system of linear equations will be created.

$$\begin{aligned} &U_1 - pL.i_3(p) + pL.i_3(0_-) - R_1.i_1(p) = 0 \\ &-pL.i_3(p) + pL.i_3(0_-) - R_{1'}.i_{1'}(p) = 0 \\ &i_3(p) = i_1(p) + i_{1'}(p) \end{aligned} \quad (8)$$

On the basis of mentioned system the equation for current $i_3(p)$ will be derived,

$$i_3(p) = \frac{p}{p + \frac{R_1}{L\left(1 + \frac{R_1}{R_{1'}}\right)}}.i_3(0_-) + \frac{U_1}{R_1}.\frac{\frac{R_1}{L\left(1 + \frac{R_1}{R_{1'}}\right)}}{p + \frac{R_1}{L\left(1 + \frac{R_1}{R_{1'}}\right)}} \quad (9)$$

where $i_3(0-)$ is current value of inductance L at the moment nearly before the feeding voltage change from value $U_{1'}$ to zero. By back transformation of above mentioned relation to the time domain and after initial condition $i_3(0-)= U_1/R_1+ U_{1'}/R_{1'}$ substitution the following equation is possible to receive.

$$i_3 = \frac{U_1}{R_1} + \frac{U_{1'}}{R_{1'}}.e^{-\frac{R_1 R_{1'}}{L(R_1 + R_{1'})}.t} \quad (10)$$

By load voltage u_2 expression is able to investigate the influence of second circuit to first one activity, caused by galvanic coupling existence.

$$u_2 = U_1 - u_L = U_1 - L.\frac{di_3}{dt} = U_1 + U_{1'}.\frac{R_1}{(R_1 + R_{1'})}.e^{-\frac{R_1 R_{1'}}{L(R_1 + R_{1'})}.t} \quad (11)$$

From obtained relation it is clear, that the first circuit load voltage is changed about value $(U_{1'}.R_1)/(R_1+R_{1'})$ in due to change existence inside the circuit, which is galvanic connected with him. None working activity of first circuit was done and so its switch on steady state remains. In dependence on load resistor values ratio the voltage drop can be within the open interval $(0,U_{1'})$.

If the supply voltage switching on state inside the second circuit will be investigated, so the information about voltage load u_2 could be obtained by similar method.

$$u_2 = U_1 - u_L = U_1 - L.\frac{di_3}{dt} = U_1 - U_{1'}.\frac{R_1}{(R_1 + R_{1'})}.e^{-\frac{R_1 R_{1'}}{L(R_1 + R_{1'})}.t} \quad (12)$$

It is evident that the load voltage value inside the first circuit can be changed about voltage drop within the open interval $(-U_{1'},0)$, again in dependence on load resistor values ratio.

Generally, the switching process inside the second circuit is through galvanic coupling reflected to the total possible load voltage u_2 change within the interval range $(-U_{1'}, U_{1'})$, depending on load values ratio and sign of derivation of current flowed via common conductor inductance L.

2.2. One common conductor – simulation and measuring

Computer numerical simulation realized by PSPICE program utilizing help us to verify the dependencies obtained analytically. Let the common conductor length is l = 0,1 m. The influence of its magnetic field in distance d = 1 m will be taken into account. Radius of cooper conductors is R = 0,6 mm and its relative permeability is μ_r = 0,991.

$$\begin{aligned} L &= L_e + L_i = \frac{\mu_0 l}{\pi}\ln\frac{d-R}{R} + \frac{\mu.l}{8\pi} = \\ &= \frac{4\pi.10^{-7}.0{,}1}{\pi}\ln\frac{1-0{,}0006}{0{,}0006} + \frac{0{,}991.4\pi.10^{-7}.0{,}1}{8\pi} \\ &= 302 \ \text{nH} \end{aligned} \quad (13)$$

In the next step will be supposed that voltage $u_{1'}$ have rectangle shape with amplitude 70 V, duty factor z = 0,5 and switching frequency f = 10 kHz.

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The rest circuit parameters are $R_{1'}$ = 11,66 Ω, U_1 = 5 V, R_1 = 10 kΩ and L = 302 nH. Based on derived equations and given parameters we can calculate the voltage u_2 peaks so, that the time in the equations (11) and (12) will be replaced by $t = 0$. Then we can obtain:

$$u_2(t_{swoff}) = U_1 + U_{1'} \cdot \frac{R_1}{(R_1 + R_{1'})} = 5 + 70.\frac{10000}{10011{,}66} = 74{,}918\,\mathrm{V} \quad (14)$$

Analogically is possible to state voltage u_2 peak at the moment of second circuit switching on.

$$u_2(t_{sw\,on}) = U_1 - U_{1'} \cdot \frac{R_1}{(R_1 + R_{1'})} = 5 - 70.\frac{10000}{10011{,}66} = -64{,}918\,\mathrm{V} \quad (15)$$

Courses of input voltages u_1 and $u_{1'}$, load voltages u_2 and $u_{2'}$ and voltage u_L are introduced in figure Fig. 3. All data was obtained by computer circuit simulation in PSPICE program for given circuit parameters. The coincidence of results obtained analytically as equations derived in previous parts and by computer numerical simulation is evident on the first sight. From the courses reached by the both methods is evident that the galvanic coupling influence between individual investigated electrical circuits is respectable and that in the case of real converter circuits or its parts utilizing it can cause serious problems with total system functionality or evently the damage of their overvoltage sensitive electronic circuits.

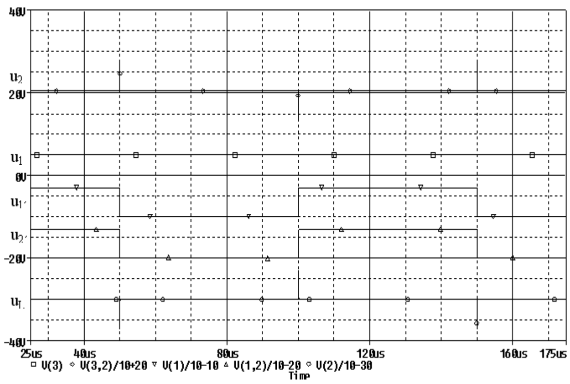

Fig. 3 Results obtained by simulation in PSPICE program

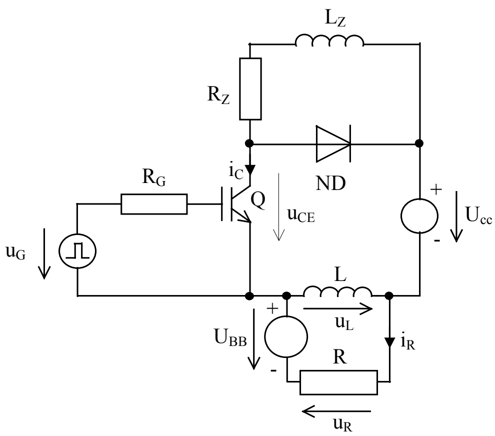

Fig. 4 Connection of simulated and measured circuit

Let the derived results verification will be done by simulation and practical measuring of the power semiconductor converter circuit connected according the scheme shown in figure Fig. 4. Circuit parameters are: U_{CC} = 70 V, R_Z = 11,66 Ω, L_Z = 400 μH, L = 302 nH, R = 10 kΩ, U_{BB} = 5 V. Power IGBT transistor is switching with frequency 10 kHz and duty cycle z = 0,5.

Courses of transistor voltage u_{CE}, inductance voltage u_L and resistance R voltage u_R obtained by simulation for frequency f = 10 kHz are pictured in figure Fig. 5. In this case the voltage jump does not

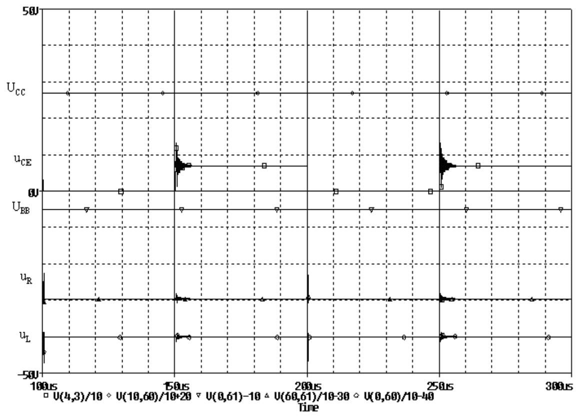

Fig. 5 Results obtained by simulation in PSPICE program

exist because the transistor is switching by finite velocity. On the basis of this fact the switching inductance voltage drop is reaching values approximately ±10 V in dependence on the current rising or falling slope. The most expressive inductance voltage drop is appearing at the moment of transistor current falling caused by charge of commutation diode existence. In this time the current slope is markedly increasing and so the parasitic inductance voltage drop is increasing too. Comparable results obtained by verification measurement are displayed in figure Fig. 6. The coincidence with the simulation results is evident.

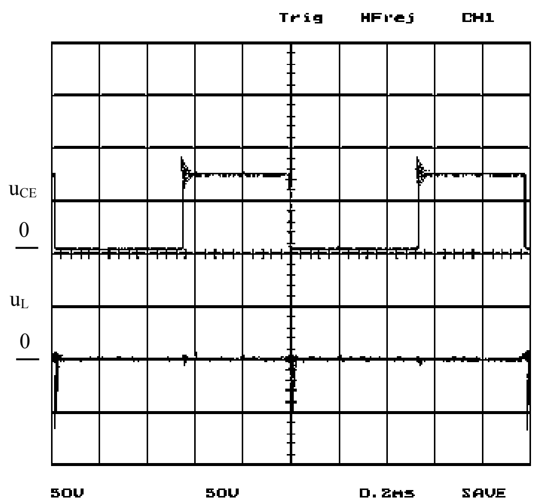

Fig. 6 Results obtained by measurement

2.3. Two common conductors - theoretical analysis

The multiple interconnection of electrical or electronics circuits realized by two common conductors is typical especially for one phase or DC feeding conductors so as it is shown in figure Fig. 7.

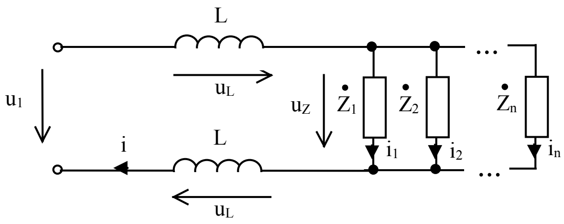

Fig. 7 Basic scheme of two conductors circuit interconnection

In due to both incoming conductor inductance *L* existence the total circuit inductance is double. The mutual galvanic coupling is generated at the moment of optional loop impedance change. The impedance can by changed up or down. This situation is typical for impulse converter circuits, but it is clear that such case is occurring also in all circuits, which are utilizing the switching parts. Circuits, the scheme of which is shown in figure Fig. 8, will serve for

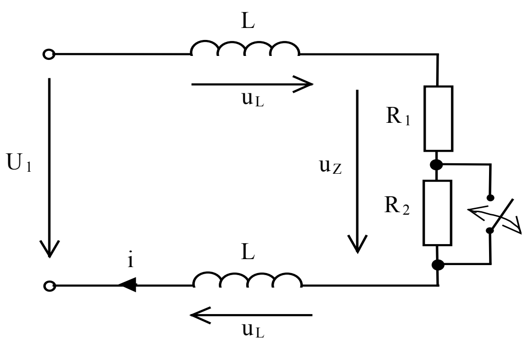

Fig. 8 Investigated circuit

investigation of the effect of such switching on the rest circuits. Let the load voltage will be investigated at the moment of parallel to resistor R_2 connected circuit closer switching on and then switching off. By Laplace – Carson transformation it is possible to write equation for investigated loop:

$$U_1 - 2pL.i(p) + 2pL.i(0_-) - R_1.i(p) = 0 \tag{16}$$

For the current inside the loop is valid relation:

$$i(p) = \frac{p}{p + \frac{R_1}{2L}}.i(0_-) + \frac{U_1}{R_1}.\frac{\frac{R_1}{2L}}{p + \frac{R_1}{2L}} \tag{17}$$

By back transformation into time domain is possible to obtain expression:

$$i = \frac{U_1}{(R_1 + R_2)}.e^{-\frac{R_1}{2L}.t} + \frac{U_1}{R_1}.\left(1 - e^{-\frac{R_1}{2L}.t}\right) \tag{18}$$

For load voltage u_Z at the moment of circuit closer switching on is valid:

$$u_z = R_1.i = U_1.\frac{R_1}{(R_1 + R_2)}.e^{-\frac{R_1}{2L}.t} + U_1.\left(1 - e^{-\frac{R_1}{2L}.t}\right) \tag{19}$$

Analogically can be derived the relation for load voltage u_Z at the moment of circuit closer switching off:

$$u_z = (R_1 + R_2).i = U_1.\frac{(R_1 + R_2)}{R_1}.e^{-\frac{(R_1+R_2)}{2L}.t} + U_1.\left(1 - e^{-\frac{(R_1+R_2)}{2L}.t}\right) \tag{20}$$

On the basis of obtained relations is possible to find out that overvoltage size caused by other electrical circuit activity can reach also very important values in dependence on individual circuit impedances ratio.

2.4. Two common conductors – simulation and measuring

The obtained knowledge correctness verification can be done by simulation in PSPICE program for following circuit parameters U_1 = 70 V, R_1 = 11,66 Ω, R_2 = 100 Ω, L = 302 nH, f = 10 kHz and duty cycle of switching z = 0,5.

By given parameters and equations derived in previous is possible to calculate the voltage u_z peaks so, that in the last equations describing voltage u_z the time will be substituted by $t = 0$.

$$u_z(t_{swon}) = U_1.\frac{R_1}{(R_1 + R_2)} + U_1.(1-1) = 70.\frac{11{,}66}{11{,}66 + 100} = 7{,}309\ \text{V} \tag{21}$$

Analogically can be derived the amplitude of voltage u_Z peak at the moment of circuit closer switching off.

$$u_z(t_{swoff}) = U_1.\frac{(R_1 + R_2)}{R_1}.1 + U_1.(1-1) = 70.\frac{(11{,}66 + 100)}{11{,}66} = 670{,}343\ \text{V} \tag{22}$$

Results obtained by simulation and corresponding measurements are pictured in figures Fig. 9 and Fig. 10.

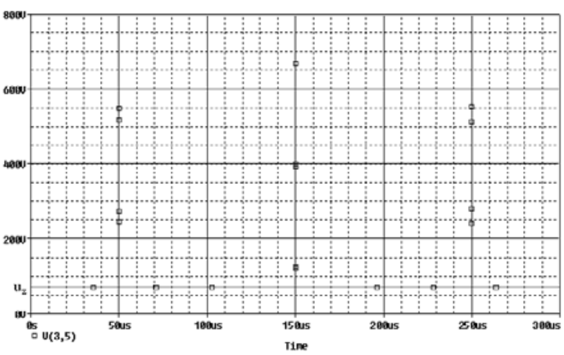

Fig. 9 Results obtained by simulation in PSPICE program

By courses comparing is possible to find out that in all tree cases was reached the same result. It means that derived equations are correct and can be utilized for predictive stating of galvanic coupling influences.

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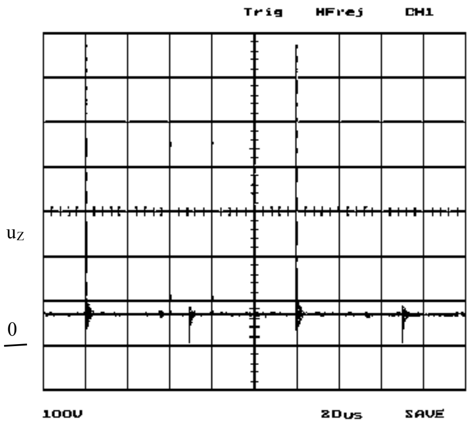

Fig. 10 Results obtained by measurement

2.5. Several common conductors - theoretical analysis

Interconnecting of many electrical or electronics circuits by several common conductors is typical for three phase feeding net as it is shown in figure Fig. 11. In the case when four conductors will do those circuits interconnection and also if one of them is neutral wire, so the problem will be the same as problem of three individual circuits connected together by only one common conductor. This problem was analyzed yet in the first part of this paper.

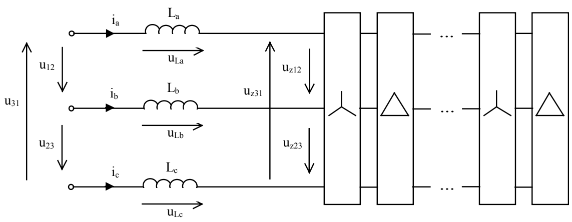

Fig. 11 Basic scheme of galvanic interconnection of more circuits by several common conductors

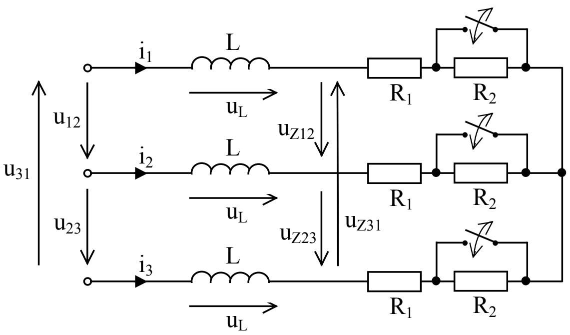

Fig. 12 Analyzed circuit

The investigation of three-phase (three conductors) galvanic coupling influence can be done by analysis of the circuit displayed in figure Fig. 12. The scheme is representing three- phase AC feeding system with long feed conductors, which is supplying time variable resistive load. Resistive load is chosen in due to request for the worst possible problem analyze. During analysis the symmetrical load will be supposed and also the condition that all three snappers will be turned on and turned off at the same time.

Let the steady state with the turn off switchers will be considered according circuit pictured in figure Fig. 12. Now, all switchers will be turned on at certain moment. The circuit can be described by the next system of equations.

$$\begin{aligned} u_{12} &= L.\frac{di_1}{dt} + R_1.i_1 - R_1.i_2 - L.\frac{di_2}{dt} \\ u_{23} &= L.\frac{di_2}{dt} + R_1.i_2 - R_1.i_3 - L.\frac{di_3}{dt} \\ i_1 + i_2 + i_3 &= 0 \end{aligned} \tag{23}$$

After its repeated transformation the system of linear equations can be obtained.

$$\begin{aligned} &\dot{U}_{12}.\frac{p}{p-j\omega} = pLi_1(p) - pLi_1(0-) + R_1.i_1(p) - \\ &- R_1.i_2(p) - pLi_2(p) + pLi_2(0-) \\ &\dot{U}_{23}.\frac{p}{p-j\omega} = pLi_2(p) - pLi_2(0-) + R_1.i_2(p) - \\ &- R_1.i_3(p) - pLi_3(p) + pLi_3(0-) \\ &i_1(p) + i_2(p) + i_3(p) = 0 \end{aligned} \tag{24}$$

By currents $i_2(p)$ and $i_1(p)$ expressing and by its substituting inside the first equation one can receive relation for current $i_3(p)$.

$$i_3(p) = \frac{-2\dot{U}_{23} - \dot{U}_{12}}{3(R_1 + pL)}.\frac{p}{p-j\omega} + i_3(0-).\frac{p}{\frac{R_1}{L}+p} \tag{25}$$

The rest currents $i_2(p)$ and $i_1(p)$ can be calculated by the next substituting.

$$i_2(p) = \frac{\dot{U}_{23} - \dot{U}_{12}}{3(R_1 + pL)}.\frac{p}{p-j\omega} + i_2(0-).\frac{p}{\frac{R_1}{L}+p} \tag{26}$$

$$i_1(p) = \frac{\dot{U}_{23} + 2\dot{U}_{12}}{3(R_1 + pL)}.\frac{p}{p-j\omega} + i_1(0-).\frac{p}{\frac{R_1}{L}+p} \tag{27}$$

Now, individual load voltages stating is possible to do on the base of calculated currents.

$$\dot{U}_{Z12}(p)=R_1.(i_1(p)-i_2(p))=\dot{U}_{12}.\frac{\frac{R_1}{L}}{\frac{R_1}{L}+p}.\frac{p}{p-j\omega}+R_1(i_1(0-)-i_2(0-)).\frac{p}{\frac{R_1}{L}+p} \tag{28}$$

$$\dot{U}_{Z23}(p)=R_1.(i_2(p)-i_3(p))=\dot{U}_{23}.\frac{\frac{R_1}{L}}{\frac{R_1}{L}+p}.\frac{p}{p-j\omega}+R_1(i_2(0-)-i_3(0-)).\frac{p}{\frac{R_1}{L}+p} \tag{29}$$

$$\dot{U}_{Z31}(p)=R_1.(i_3(p)-i_1(p))=\dot{U}_{31}.\frac{\frac{R_1}{L}}{\frac{R_1}{L}+p}.\frac{p}{p-j\omega}+R_1(i_3(0-)-i_1(0-)).\frac{p}{\frac{R_1}{L}+p} \tag{30}$$

After back transformation to time domain the system will be given as:

$$\dot{U}_{Z12}(j\omega t)=\dot{U}_{12}.e^{j\omega t}.\frac{R_1}{R_1+j\omega L}-\dot{U}_{12}.e^{-\frac{R_1}{L}t}.\frac{R_1}{R_1+j\omega L}+R_1(i_1(0-)-i_2(0-))e^{-\frac{R_1}{L}t} \quad (31)$$

$$\dot{U}_{Z23}(j\omega t)=\dot{U}_{23}.e^{j\omega t}.\frac{R_1}{R_1+j\omega L}-\dot{U}_{23}.e^{-\frac{R_1}{L}t}.\frac{R_1}{R_1+j\omega L}+R_1(i_2(0-)-i_3(0-))e^{-\frac{R_1}{L}t} \quad (32)$$

$$\dot{U}_{Z31}(j\omega t)=\dot{U}_{31}.e^{j\omega t}.\frac{R_1}{R_1+j\omega L}-\dot{U}_{31}.e^{-\frac{R_1}{L}t}.\frac{R_1}{R_1+j\omega L}+R_1(i_3(0-)-i_1(0-))e^{-\frac{R_1}{L}t} \quad (33)$$

For general voltage expression the calculation of initial current conditions must be done at the moment nearly before turn on of snappers. They can be calculated from the next system of equations.

$$\dot{U}_{12}=j\omega L\dot{I}_1+(R_1+R_2).\dot{I}_1-(R_1+R_2).\dot{I}_2-j\omega L\dot{I}_2 \quad (34)$$

$$\dot{U}_{23}=j\omega L\dot{I}_2+(R_1+R_2).\dot{I}_2-(R_1+R_2).\dot{I}_3-j\omega L\dot{I}_3 \quad (35)$$

$$\dot{I}_1+\dot{I}_2+\dot{I}_3=0 \quad (36)$$

The following relations will be obtained after previous system solving:

$$\dot{I}_1=\frac{2\dot{U}_{12}+\dot{U}_{23}}{3((R_1+R_2)+j\omega L)} \quad (37)$$

$$\dot{I}_2=\frac{\dot{U}_{23}-\dot{U}_{12}}{3((R_1+R_2)+j\omega L)} \quad (38)$$

$$\dot{I}_3=\frac{-2\dot{U}_{23}-\dot{U}_{12}}{3((R_1+R_2)+j\omega L)} \quad (39)$$

For individual current differences, expressed by complex phasor, will be valid:

$$\dot{I}_1-\dot{I}_2=\frac{\dot{U}_{12}}{(R_1+R_2)+j\omega L} \quad (40)$$

$$\dot{I}_2-\dot{I}_3=\frac{\dot{U}_{23}}{(R_1+R_2)+j\omega L} \quad (41)$$

$$\dot{I}_3-\dot{I}_1=\frac{\dot{U}_{31}}{(R_1+R_2)+j\omega L} \quad (42)$$

The resulting relations for load voltages, expressed by rotating complex phasors, then will have form,

$$\dot{U}_{Z12}(j\omega t)=U_{12}e^{j\varphi_U}.(\frac{R_1}{e^{j\varphi_{Z1}}.\sqrt{(R_1)^2+(\omega L)^2}}(e^{j\omega t}-e^{-\frac{R_1}{L}t})+e^{-\frac{R_1}{L}t}.\frac{R_1}{e^{j\varphi_{Z2}}.\sqrt{(R_1+R_2)^2+(\omega L)^2}}) \quad (43)$$

$$\dot{U}_{Z23}(j\omega t)=U_{23}e^{j\varphi_U-120^\circ}.(\frac{R_1}{e^{j\varphi_{Z1}}.\sqrt{(R_1)^2+(\omega L)^2}}(e^{j\omega t}-e^{-\frac{R_1}{L}t})+e^{-\frac{R_1}{L}t}.\frac{R_1}{e^{j\varphi_{Z2}}.\sqrt{(R_1+R_2)^2+(\omega L)^2}}) \quad (44)$$

$$\dot{U}_{Z31}(j\omega t)=U_{31}e^{j\varphi_U+120^\circ}.(\frac{R_1}{e^{j\varphi_{Z1}}.\sqrt{(R_1)^2+(\omega L)^2}}(e^{j\omega t}-e^{-\frac{R_1}{L}t})+e^{-\frac{R_1}{L}t}.\frac{R_1}{e^{j\varphi_{Z2}}.\sqrt{(R_1+R_2)^2+(\omega L)^2}}) \quad (45)$$

where

$$\varphi_{Z1}=arctg\ \frac{\omega L}{R_1} \quad (46)$$

$$\varphi_{Z2}=arctg\ \frac{\omega L}{R_1+R_2} \quad (47)$$

$$\varphi_U=\frac{360^\circ.\omega.t(0)}{2\pi} \quad (48)$$

On the basis of performed analysis is evident, that if the resistive load represented by resistors R_2 will have bigger value in comparison of load resistor R_1 values, so the bigger will be also the load voltages fall at the moment of snappers turn on *t(0)*. In extreme cases the load voltages can be approaching to the value 0 V during the very short time, which is depending on circuit time constant.

Analogically to previous method the relations for load voltages at the moment of turn off of snappers can be derived.

$$\dot{U}_{Z12}(j\omega t)=U_{12}.e^{j\varphi_U}.(\frac{(R_1+R_2)}{e^{j\varphi_{Z2}}.\sqrt{(R_1+R_2)^2+(\omega L)^2}}(e^{j\omega t}-e^{-\frac{(R_1+R_2)}{L}t})+ +e^{-\frac{(R_1+R_2)}{L}t}.\frac{(R_1+R_2)}{e^{j\varphi_{Z1}}.\sqrt{(R_1)^2+(\omega L)^2}}) \quad (49)$$

$$\dot{U}_{Z23}(j\omega t)=U_{23}.e^{j\varphi_U-120^\circ}.(\frac{(R_1+R_2)}{e^{j\varphi_{Z2}}.\sqrt{(R_1+R_2)^2+(\omega L)^2}}(e^{j\omega t}-e^{-\frac{(R_1+R_2)}{L}t})+ +e^{-\frac{(R_1+R_2)}{L}t}.\frac{(R_1+R_2)}{e^{j\varphi_{Z1}}.\sqrt{(R_1)^2+(\omega L)^2}}) \quad (50)$$

$$\dot{U}_{Z31}(j\omega t)=U_{31}.e^{j\varphi_U+120^\circ}.(\frac{(R_1+R_2)}{e^{j\varphi_{Z2}}.\sqrt{(R_1+R_2)^2+(\omega L)^2}}(e^{j\omega t}-e^{-\frac{(R_1+R_2)}{L}t})+ +e^{-\frac{(R_1+R_2)}{L}t}.\frac{(R_1+R_2)}{e^{j\varphi_{Z1}}.\sqrt{(R_1)^2+(\omega L)^2}}) \quad (51)$$

From obtained equations is possible to deduce, that if the resistor R_2 values will be much bigger as resistor R_1 values, so the largeness of load voltages will be much bigger in comparison to the instantaneous value of nominal feeding voltage.

2.6. Several common conductors – simulation and measuring

The derived equations correctness will be verified in following by PSPICE program simulation. Investigated circuit parameters are $U_{12} = U_{23} = U_{31} = 400$ V, $R_1 = 10\ \Omega$, $R_2 = 100\ \Omega$, $\varphi_U = 90° + \varphi_{Z1}$, $L = 800$ nH, $f = 50$ Hz. At the moment of snappers turn on the voltage u_{12} value will be given as:

$$\dot{U}_{Z12}(j\omega t(0))=U_{12}.e^{j\varphi_U}.\frac{R_1}{e^{j\varphi_{Z2}}.\sqrt{(R_1+R_2)^2+(\omega L)^2}} \quad (52)$$

$$u_{Z12}=400.\sqrt{2}.\sin(90^\circ+0{,}00144^\circ-0{,}000131^\circ).\ .\frac{10}{\sqrt{12100+63.10^{-9}}}=51{,}42\ \text{V} \quad (53)$$

The voltage u_{12} value at the moment of snappers turn off will be:

$$\dot{U}_{Z12}(j\omega t(0))=U_{12}.e^{j\varphi_U}.\frac{(R_1+R_2)}{e^{j\varphi_{Z1}}.\sqrt{(R_1)^2+(\omega L)^2}}) \quad (54)$$

$$u_{Z12} = 400.\sqrt{2}.\sin(90^o).\frac{110}{\sqrt{100+63.10^{-9}}} = 6222{,}52\ \text{V} \qquad (55)$$

Comparable courses obtained by simulation in PSPICE program are shown in following figure Fig. 13. By analytical and simulation voltage value comparing at the moments of snappers turn on and turn off is possible find out that results are identical. Based on above-mentioned, the fact that derived equations are valid is resulting and so they can be utilized by electrical equipment constructers for construction vision creation concerning of galvanic coupling influences caused by three-phase (three conductors) feeding net.

Results of practical verification measuring, which are confirming the correctness of theoretical results, are displayed in figure Fig. 14.

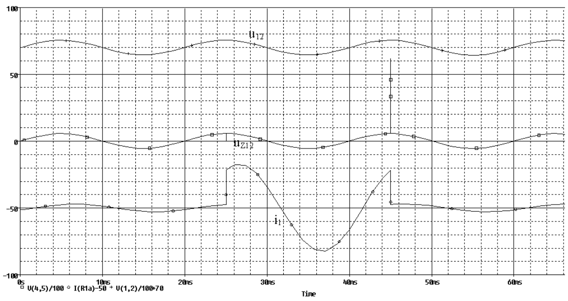

Fig. 13 Courses obtained by simulation

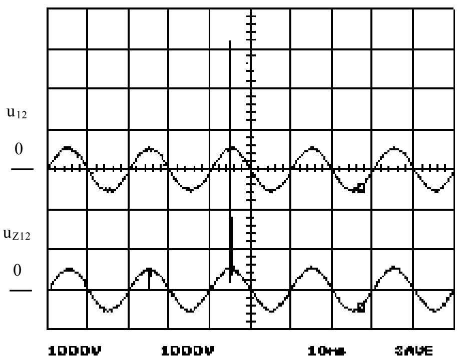

Fig. 14 Results obtained by circuit measuring

3. CONCLUSION

All performed analyzes indicates that derived equations are correct and so can be utilized for predictive stating of galvanic coupling influences. Based on above-mentioned, the fact that derived equations are valid is resulting to the conclusion that they can be utilized by electrical equipment constructers for construction vision creating, which is concerning of galvanic coupling influences.

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BIOGRAPHIES

Kováčová Irena - She finished her studies in 1982 at the Technical University of Košice, Department of Electrical Drives, direction - Power electronics with excellent evaluation. From this time she has worked at the Department of Electrical Drives, first as assistant lecturer and now as associate professor. In 1988 she has got her doctoral diploma. In 1991 she has got the Award of Minister of Education for Development of Science and Technology. Her working interest is mainly focused to the field of power electronics, especially to the construction of converters and inverters with new perspective elements and computer simulation of new power semiconductor parts and devices.

Ján Kaňuch - He finished his studies in 1986 at the Technical University of Košice, Department of Electrical Drives and direction – Electrical machines. From this time he has worked at the Department of Electrical Drives as assistant lecturer. His working interest is mainly focused to the field of construction of electrical machines, electrical equipments for motor-cars and electrical apparatuses.

Kováč Dobroslav - He finished his studies in 1985 at the Technical University of Košice, Department of Electrical Drives, direction - Power electronics with excellent evaluation. Then he worked as research worker at the Department of Electrical Drives. His research work was focused to the practical application of new power semiconductor devices. In 1989 he has got the Award of Minister of Education for Development of Science and Technology. From 1991 he has worked as assistant lecturer at the Department of Theoretical electrical engineering and Electrical measurement. He got his doctoral diploma in 1992 for the work on the field of power electronics. From 2000 he worked as professor and his working interest is now focused mainly to the field of computer simulation of power electronic circuits and automated computer measuring.