Abstract This paper deals with an analysis of the electromagnetic compatibility (EMC) – galvanic coupling problems focused on the area of power electrical systems. The description of galvanic coupling problem is divided into the separate parts according to the length of common conductors or working frequency. The fourth part (PART IV.) of the work analyses a problem of circuits with distributed parameters, which have several conductors or process high frequency signals. We have used a mathematical analysis, computer simulation method and verification of measurements for detailed investigation of this area.

Key words: electromagnetic compatibility, galvanic coupling, common conductors, long lines.

1. Introduction

Importance of electromagnetic compatibility (EMC) of all electrical products has been rapidly growing during the last decade [1], [2], [3], [4], [5], [6]. The living environment is increasingly polluted by electromagnetic energy. The interference impact on the surroundings is being doubled every three years and covers a large frequency range [7], [8], [9], [10]. Equipment disturbances and errors have become more serious as a consequence of the growth of the electronic circuit complexity [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21]. According to a new technical legislation and also due to economic consequences, the EMC concept of all products must be strictly observed [22], [23], [24]. It must start with the specification of the equipment performance and end with the equipment installation procedures.

We use computer simulation to investigate EMC of electrical products with different types and difficulty levels instead of time-consuming theoretical analysis or costly experiments [25], [26].

The contribution of this paper consists of derivation of relations valid for non-harmonic inverter’s output voltage connected to the load by three-phase cable. The solution for the higher frequencies and distributed parameters are presented in the following chapter 2. The theoretical analysis is discussed in subchapter 2.1. The simulation and measuring of parameters are demonstrated in subchapter 2.2. The last chapter 3 consists of the conclusions.

2. Solution for the Higher Frequencies and Distributed Parameters

The working frequencies and the length of common conductors must be always taken into the 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. Due to existence of the contents of higher harmonics in currents that flow across the common conductors, such circuits 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. Theoretical analysis - several conductors

In the practical exploitation of power semiconductor converters a very often case occurs when symmetric three-phase load is connected to the inverter impulse output with the frequency of few tenths of kHz by the cable that is 3 to 20 m long. Such topology represents the three-phase interconnection of two circuits by a long line with the distributed parameters, as is shown on Fig. 1.
The investigation of galvanic coupling of such circuit can be done by calculation of the output voltages $u_{12}$, $u_{23}$, and $u_{31}$ at the end of a long transmission line. The input voltages are graphically shown on Fig. 2.

![Fig. 2. The input voltages $u_{12}$, $u_{23}$ and $u_{31}$](image)

The amplitudes of the input voltages are $U = 400$ V. The interconnecting cable with the parameters was used: CYSY 4x1.5 mm², with the length 15m, $R_0 = 0.047 \, \Omega/m$, $L_0 = 343 \, nH/m$, $G_0 = 33.3 \, \mu S/m$, $C_0 = 118 \, pF/m$. The load is symmetric with parameters: $R_2 = 10 \, \Omega$, $L_2 = 1 \, mH$.

To calculate the output voltages $u_{12}$, $u_{23}$, and $u_{31}$, the equations derived from previous analyses [27], [28] can be used. However, the feeding of non-harmonic input voltages is necessary to express using harmonic functions. The Fourier’s series [29] will be used again.

1. $a_n = \frac{1}{T} \int_0^{T/2} U \cdot dt + \frac{1}{T} \int_{T/2}^T -U \cdot dt = 0$ (1)

2. $a_k = \frac{2}{T} \int_0^{T/2} U \cdot \cos(k\omega t) \cdot dt + \frac{2}{T} \int_{T/2}^T -U \cdot \cos(k\omega t) \cdot dt = \frac{U}{k\pi} ((\sin(k\pi) - \sin(0)) - (\sin(k2\pi) - \sin(k\pi))) = 0$ (2)

3. $b_k = \frac{2}{T} \int_0^{T/2} U \cdot \sin(k\omega t) \cdot dt + \frac{2}{T} \int_{T/2}^T -U \cdot \sin(k\omega t) \cdot dt = -\frac{U}{k\pi} ((\cos(k\pi) - 1) - (\cos(k2\pi) - \cos(k\pi))) = \frac{4U}{(2k+1)\pi}$ (3)

4. $u_n(t) = \frac{4U}{\pi} \sin(\omega t) + \frac{4U}{3\pi} \sin(3\omega t) + \frac{4U}{5\pi} \sin(5\omega t) + ... = \sum_{k=0}^{\infty} \frac{4U}{(2k+1)\pi} \sin((2k+1)\omega t)$ (4)

The other two voltages are expressed consequently with regard on the translation in time.

$$u_{12}(t) = \frac{4U}{\pi} \sin(\omega t - \frac{T}{3}) + \frac{4U}{3\pi} \sin(3\omega t - \frac{T}{3}) + \frac{4U}{5\pi} \sin(5\omega t - \frac{T}{3}) + ... = \sum_{k=0}^{\infty} \frac{4U}{(2k+1)\pi} \sin((2k+1)\omega t - \frac{T}{3})$$ (5)

$$u_{23}(t) = \frac{4U}{\pi} \sin(\omega t - \frac{2T}{3}) + \frac{4U}{3\pi} \sin(3\omega t - \frac{2T}{3}) + \frac{4U}{5\pi} \sin(5\omega t - \frac{2T}{3}) + ... = \sum_{k=0}^{\infty} \frac{4U}{(2k+1)\pi} \sin((2k+1)\omega t - \frac{2T}{3})$$ (6)

If the expressions calculated for the input voltages are substituted by the equation (19) derived in part I. [27], which describes the temporal dependence of the voltage at the end of the cable line, thus we can obtain the relations (7) till (9). The condition is that only the imaginary part of the complex solution will be taken into the account, because only this part corresponds to the sinusoidal input voltage.

During the calculation process, the recalculation of load impedance value (from star to triangle) must be performed, because the temporal curves of interline voltages are being searched. The MS Excel program will be used to obtain the graphical representation of the achieved results. It shows graphical results containing the first 40 components of Fourier’s series. The respective curves are drawn in Fig. 3. to Fig. 10.

![Fig. 3. Synthesis of the input voltage $u_{12}$](image)

![Fig. 4. The output voltage $u_{12}$](image)
\[ u_{12}(t) = \sum_{k=0}^{\infty} \frac{2U}{(2k+1)\pi} \left( e^{a\beta \cdot \sin((2k+1)\omega t + \varphi_U)} + e^{-a\beta \cdot \sin((2k+1)\omega t + \varphi_U - \alpha)} \right) - \frac{\sqrt{a^2 + b^2}}{\sqrt{c^2 + d^2}} e^{\beta} \cdot \sin((2k+1)\omega t + \varphi_U + \alpha + \arctg \frac{b}{a} - \arctg \frac{d}{c}) + \frac{\sqrt{a^2 + b^2}}{\sqrt{c^2 + d^2}} e^{-\beta} \cdot \sin((2k+1)\omega t + \varphi_U - \alpha + \arctg \frac{b}{a} - \arctg \frac{d}{c}) \]

\[ u_{23}(t) = \sum_{k=0}^{\infty} \frac{2U}{(2k+1)\pi} \left( e^{a\beta \cdot \sin((2k+1)\omega t - \frac{T}{3} + \varphi_U + \alpha)} + e^{-a\beta \cdot \sin((2k+1)\omega t - \frac{T}{3} + \varphi_U - \alpha)} \right) - \frac{\sqrt{a^2 + b^2}}{\sqrt{c^2 + d^2}} e^{\beta} \cdot \sin((2k+1)\omega t - \frac{T}{3} + \varphi_U + \alpha + \arctg \frac{b}{a} - \arctg \frac{d}{c}) + \frac{\sqrt{a^2 + b^2}}{\sqrt{c^2 + d^2}} e^{-\beta} \cdot \sin((2k+1)\omega t - \frac{T}{3} + \varphi_U - \alpha + \arctg \frac{b}{a} - \arctg \frac{d}{c}) \]

\[ u_{31}(t) = \sum_{k=0}^{\infty} \frac{2U}{(2k+1)\pi} \left( e^{a\beta \cdot \sin((2k+1)\omega t - \frac{2T}{3} + \varphi_U + \alpha)} + e^{-a\beta \cdot \sin((2k+1)\omega t - \frac{2T}{3} + \varphi_U - \alpha)} \right) - \frac{\sqrt{a^2 + b^2}}{\sqrt{c^2 + d^2}} e^{\beta} \cdot \sin((2k+1)\omega t - \frac{2T}{3} + \varphi_U + \alpha + \arctg \frac{b}{a} - \arctg \frac{d}{c}) + \frac{\sqrt{a^2 + b^2}}{\sqrt{c^2 + d^2}} e^{-\beta} \cdot \sin((2k+1)\omega t - \frac{2T}{3} + \varphi_U - \alpha + \arctg \frac{b}{a} - \arctg \frac{d}{c}) \]
The following two figures show the sum of all three input and output voltages. From the shape of the graphs, it is evident, that during such a choice of the feeding signal shape, the non-harmonic supply system, containing the expressive amount of 3rd harmonic voltage and its multiples, is generated.

Fig. 9. The potential of the inverter neutral node

As result of the existence of nodal potential difference the loop current, flowing via neutral wire, can be generated in the case of four-conductor circuit interconnection. However, such situation is in the contradiction to the standard requirements.

2.2. Simulation and Measuring - Several conductors

For the subsidiary verification of simulations, the MS Excel program can be utilized again. The long transmission line (cable) with the distributed parameters will be replaced by a line with concentrated parameters corresponding to its length. The simulation results are displayed in the following two figures Fig. 11. and Fig. 12.

The coincidence between the curves obtained by analytical calculation and by the computer simulation method is evident. So we can suppose that the derived relations are correct. The verified measurement results are shown in the figures Fig. 13. to Fig. 18.
3. Conclusion

The performed analysis discovers the fact that parameters of the cable that interconnects inverter and the load can have important influence on its working conditions and so also on its EMC. It also points on the existence of different potentials between the three-phase inverter neutral node and three-phase load node with the great value of the 3rd harmonics. The accuracy of all obtained results was confirmed by computer simulation and by measurements. Its mutual coincidence is evident. Derived equations enable to solve the described problem by numerical computing and computer simulation very easily. In this way it is possible to design the correct load and load filters. So it gives opportunities to improve the EMC parameters of the newly constructed devices not only by expensive testing measurements, but also using theoretical analysis and simulation tools. Based on the results introduced in this paper, the constructors can determine the EMC properties of the devices by a predictive method. Then the EMC improvement will thus be more comfortable, cheaper, easier and faster.

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