HARMONIC PROPAGATION ON OVERHEAD TRANSMISSION LINES OPERATING IN UNBALANCED POWER SYSTEMS

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Abstract. *The paper presents an estimation of harmonic voltages and currents and consideration on harmonic distortion on transmission systems. The influence on the harmonic propagation on overhead transmission lines operating in unbalanced power systems is studied according to the influence of different components.*

Among these the following components should be mentioned: power transformer (actual turn ratio, connection diagram, short-circuit impedance), overhead lines (phase angles and neutral conductor size, layout, lengths, short-circuit impedance, capacitance (when needed), capacitor bank (voltage rating, VAr rating, configuration), generator (subtransient impedance, configuration), loads (linear: watts, power factor, composition, balance and nonlinear: expected level of harmonic current injection, magnitude and phase angle).

Keywords: *harmonic analysis, harmonic voltage and currents, unbalanced power systems, modelling, overhead transmission lines*

1. INTRODUCTION

Conventionally, the definitions used to describe electric quantities for power system studies are defined for sinusoidal steady state. However, when harmonics are introduced by system nonlinearities, these definitions are obtained by modifying those appropriate for single-frequency systems.

The magnitudes and phase angles of the three-phase harmonic voltages and currents are sensitive to network or load unbalances. Even for small deviations from balanced conditions at the fundamental frequency, it has been noted that harmonic unbalance can be significant. In the unbalanced case, line currents and neutral currents can contain a rich harmonic spectrum and components of all sequences.

The *Discrete Fourier Transform* (DFT) is usually used in an harmonic study since the measured data is always available as a sampled time function. Fourier analysis can be applied using DFT. The results obtained using EMTP simulation are graphically represented. The paper presents an estimation of harmonic voltages and currents and consideration on harmonic distortion within electric systems.

2. HARMONIC SOURCES IN HIGH VOLTAGE ELECTRIC NETWORKS

In AC networks, the current and voltage are expected to be sine waves. Any deviation leads to the presence of supplementary currents and voltages having a higher frequency, which can lead to rated normal operating conditions alteration, both inside that network, as well as in its neighbouring networks

Throughout the network, the harmonic sources and the harmoniccomponents generated can be the triggering phenomenon for high level overvoltages and high currents, which can lead to insulation sparkover or breakdown or conductor overheating. And it is to be stressed that all these effects originate in high order harmonic voltages and currents, due to deviations from the expected sine waves.

Power transformers and high voltage are well known sources for high order harmonics, especially when their core is operating under saturation conditions. Magnetic saturation of the steel core is the main cause for a strong distortion of the current and voltage waves. Under a sinusoidal voltage applied to a winding, the absorbed magnetising current will have a pointed waveshape, a proof that its harmonic content is very rich.

The same situation is identified when strongly non-linear elements are presents within the network. For instance, it is known that corona discharge on the conductors of high-voltage (HV) and very high-voltage (VHV) lines is characterised by a rapid rise of the discharge current as soon as the voltage increase over a critical value.

It is this fact that explains the existence of high order harmonic current and voltages on transmission lines.

3. MODELLING AND SIMULATION OF THE ELECTRIC POWER SYSTEM

Numerical simulation /6, 7/ can be employed to anticipate the problems caused within the power system by the harmonic components and estimate the procedures to control them.

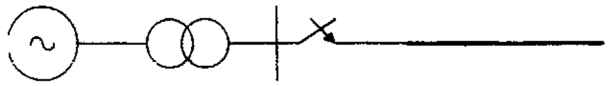

Fig. 1, *a* – Equivalent circuit for the power system.

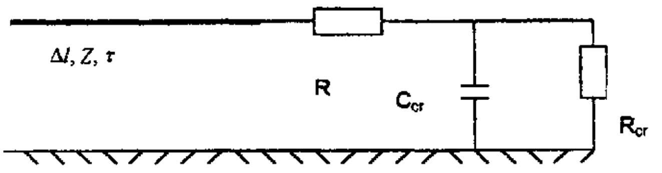

Fig. 1, *b* – Corona discharge model.

In order to determine the value of harmonic distortion, each component of the system has to be modelled as being *frequency dependent*. Recommendations are formulated for modelling the components (harmonic sources, transport and distribution lines, filters and condenser units, power transformers and different loads) and the electric network.

A harmonic study /1, 6/ base can be established when modelling every component type:

- Harmonic sources are the most important element when simulating the harmonic system. Harmonic currents can originate in a certain number of sources, including static converters, arc furnaces non-linear motors, computer networks, etc. The input data for database can be obtained experimentally or from reported data within specialised literature.

- When studying the harmonic operating conditions in case of transport and distribution lines, it is particularly important to consider their frequency dependency. Capacitive and inductive mutual coupling of lines with different rated voltage have also to be included into the model (high frequency coupling could result in resonance conditions within lower voltage lines or within telecommunication lines).

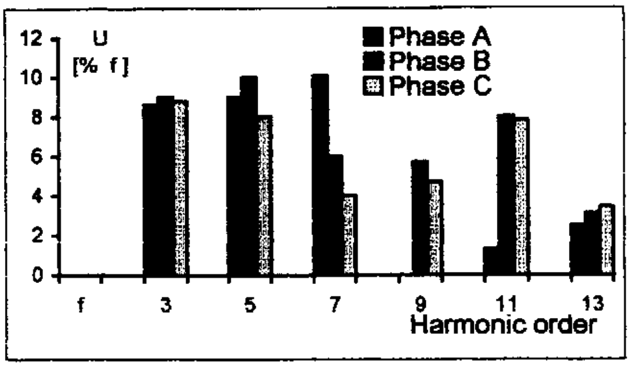

Fig. 2 - Fourier analysis
(linear characteristic, unsymmetrical operating conditions for a Romanian HV transmission line, 400 kV, 230 km).

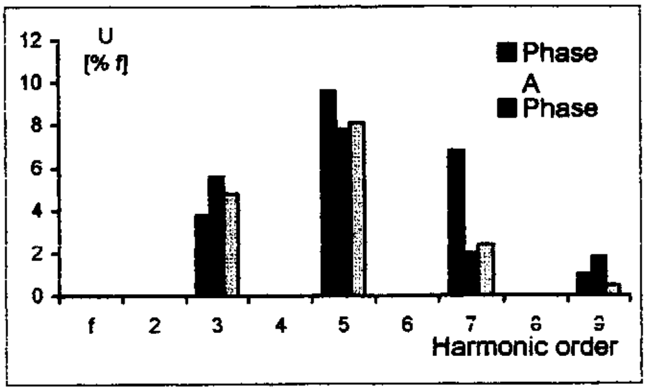

Fig. 3 - Fourier analysis for a circuit including a generating unit, a power transformer, a 400 kV transmission line and a load (non-linear characteristic, unsymmetrical operating conditions).

There are three possible modelling procedures for these effects:

- a linear model can be adopted for short lines, with the impedance considered as a linear function of frequency;
- a simplified model for long lines could employ a linear model with lumped capacitive parameters at both ends;
- the preferred model is the one including a non-linear impedance model, which considers the components with distributed parameters, skin effect, etc (Fig.1).

The difference between a linear and a non-linear model can be traced in Figures 2 and 3.

Power transformers operating in saturated conditions are modelled as harmonic sources, the process of nonlinearity generation being

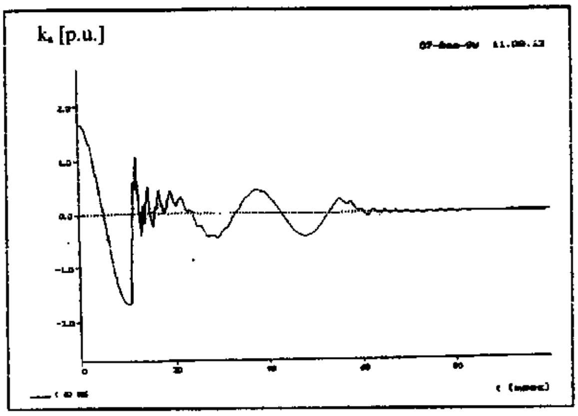

Fig. 4 - Voltage waveshape for 750 kV network, for single phase ground fault (phase A) and reclosing on remanently charged line, considering the magnetisation curve of the transformer; (line node, k_s = 1,8, detail for 0 – 100 ms).

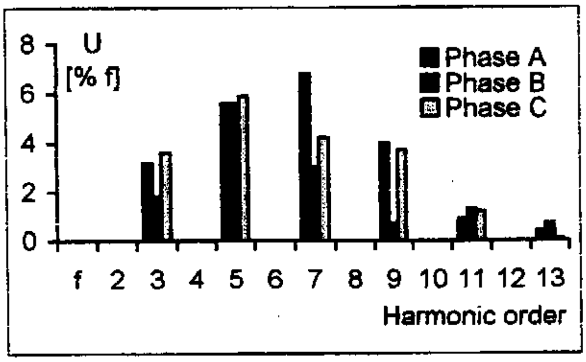

Fig. 5 – The effect of modelling high frequency coupling between two Romanian HV overhead lines:
400 kV (230 km) and 6 kV (20 km), parallelism length 3 km.

liable of a more detailed modelling by examining the flux and current waveshapes, as well as the hysteresis curve /1, 2, 8/.

4. SATURATION HARMONICS ON LONG TRANSMISSION LINES

4.1. General properties

Transformer core saturation could - in certain cases – result in voltage escalations, as a result of the presence of high order and low order harmonic components, which could be of follow-up and resonance type.

The group of follow-up harmonics are high order harmonics (with frequencies that are multiple of fundamental power frequency), of odd order, with frequencies that are 3, 5 7, ... times the fundamental one (f_s = 50 Hz). The cause responsible for their presence is the non-sine wave of the magnetisation current for a voltage higher than the rated value.

High order odd harmonics are possible under certain circumstances, with high amplitudes only in case the specific frequency of the circuit is close to the one of the considered harmonic. Resonant harmonics are only identified in case these two values are equal. The resonance components are only present in case specific frequency of the circuit (considering the saturation) equal to the considered harmonic component /1/. The circuit containing the tripped line (together with the supply source) is a complex oscillatory circuit, with a certain content of specific frequencies. This is why, in general, a resonance is possible for two frequencies, e.g. the 2nd and the 5th ones. But, such situations are not likely to occur /2/. In most cases a single frequency is dominant in the voltage waveshape and for this resonant conditions are generated.

A model study of the different circuits including long lines reveals that most of the cases present voltage escalations dependent on the presence of the 5th, 7th, 2nd components or the presence of the $f_s/3$ sub-harmonic component.

For a long line switching-in the first specific frequency, as computed without considering the core saturation, is of the order of $(1{,}4 \div 2{,}5)f_s$, favouring thus the appearance of 2nd or 3rd harmonic components. /2, 3, 6/. But 3rd order harmonic component is but rarely present as a result of two main reasons:

- The first main reason is the primary, delta-connected winding of the transformer. It is equivalent, thus, to a low inductance shunt for triple frequency; an exception is the low power transformer, having a high inductance tertiary winding.
- The second reason is a consequence of the fact that for considerable amplitude harmonics to appear it is necessary a power frequency voltage escalation on the branch representing the magnetic circuit. In case the first specific frequency is close to 3 f_s, then the voltage escalations are insignificant.

For the first specific frequency in the interval $(1{,}4 \div 2{,}5)\ f_s$, the secondary frequencies are close to $(5 \div 7)\ f_s$, favouring thus the increase of the amplitude for 5th and 7th components. The component having the frequency of $f_s / 3$ is specific to nodes with shunt compensation; its amplitude is controlled by the condenser battery and the inductance of the reactors connected to the specific line /4, 5/.

The sub-harmonic resonance was closely examined by the time the first VHV transmission line was constructed. An analogue model study /7/ revealed stable sub-harmonic components with large amplitudes, caused by the nonlinearity of the reactors (whose magnetisation curve could by described using a third degree polynome). The occurrence of these oscillations in real conditions was excluded on the basis of the diminished nonlinearity of the reactors and of the design of a proper substation circuit and proper location of the switching equipment.

In a detailed study of the harmonic components to identify their influence on overvoltage magnitudes, the dependence $U_{\mu k} = f(I_{\mu k})$ should be determined, this is a volt-ampere characteristic for the considered harmonic component. The power frequency component and the shape of the applied voltage influence the shape of this curve.

Obtaining these curves, using a Fourier representation of the current waveshapes for different voltage waveshapes over the magnetic circuit branch, the harmonic components could be determined in a specific network..

4.2. Determining the follow-up harmonics (5^{th} harmonic)

The basic hypothesis adopts a flux wave containing the power frequency component and only one other harmonic component. The presence of two components with very close specific frequencies is less probable, but not excluded. So, neglecting the losses, one can accept that:

$$\Psi = \Psi_1 \sin \omega_s t \pm \Psi_k \sin \omega_s t \,. \qquad (4.1)$$

A Fourier analysis of the magnetising current wave reveals that for $k = 5$ or 7 and $\psi_k \le 0{,}1\,\psi_1$, the fundamental frequency of magnetising current is practically independent of the content of high order components.

Figure 6 presents *the dependence of the 5^{th} harmonic component of the magnetising current on the fundamental component amplitude, for a flux wave that is sinusoidal or contains the 5^{th} harmonic component.*

For known dependence $I_{\mu k} = f\,(\psi_1)$ for different values of the ratio $\frac{\Psi_k}{\Psi_1}$, for each ψ_1 value the curves $U_{\mu k} = \frac{d\Psi_k}{dt} = k\omega_s \Psi_1 = f(I_{\mu k})$ could be obtained.

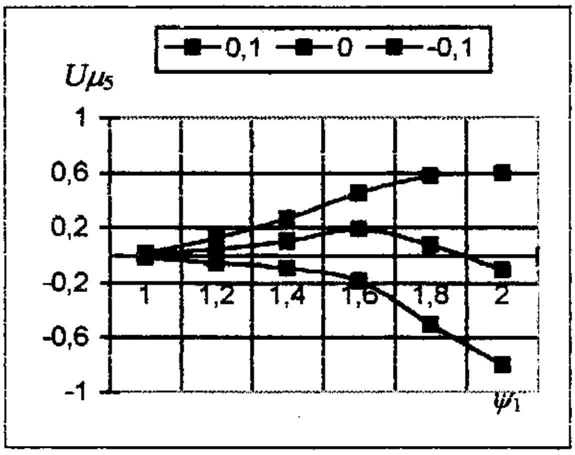

Fig. 6 – Dependence of the 5^{th} harmonic component of the magnetising current on the fundamental component amplitude.

Figures 7, *a* and *b* present $E_{\mu 5} = f\,(\psi_1)$ and $x_{\mu 5} = f(\psi_1)$ for the magnetic circuit of a transformer considered as a high order harmonic generator. It is supposed that $E_{\mu k}$ remains constant, while $x_{\mu k}$ varies inversely proportional with the power. Using the data in Figure 6 the 5^{th} component could be study for a circuit of high complexity.

The impedance Z_k of external circuit offered to that *k*-th component is obtained by a parallel connection of the inductive impedance $Z_{sk} = j\,kx_s$ and the input impedance of the line (with the transformer at the input end of the line):

$$Z_k = \frac{Z_{sk} \cdot Z_{vxk}}{Z_{sk} + Z_{vxk}} = r_k \pm jx_k \,. \qquad (4.2)$$

The impedance Z_k can be of inductive or capacitive nature, according to the line length and the value of the source impedance. When neglecting the losses, the voltage component over the magnetic circuit is equal to:

$$\underline{U}_{\mu k} = \underline{E}_{\mu k} \frac{\pm jx_k}{jx_{\mu k} \pm jx_k + r_k} \,. \qquad (4.3)$$

Eq. (4.3) shows that the value of the harmonic component $U_{\mu k}$ depends on saturation, as well as on rated power of the transformer and the circuit parameters. This component reaches its maximum value in case the imaginary part of the denominator in Eq. (4.3) vanishes, this is when the input impedance of the circuit against the magnetic circuit connection point is of a capacitive nature and equal to the internal impedance of the equivalent generator. The amplitude of this component is loss-dependent. Moreover, as it will be shown in a study for the 2nd harmonic component, for large values of $U_{\mu k}$ the influence of high order components on the power frequency components should also be considered.

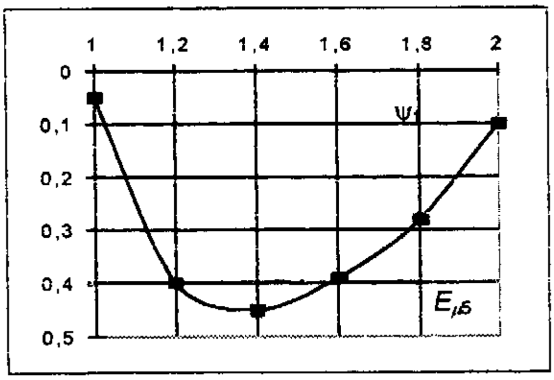

Fig. 7, *a* - Dependence of $E_{\mu 5}$ on ψ_1.

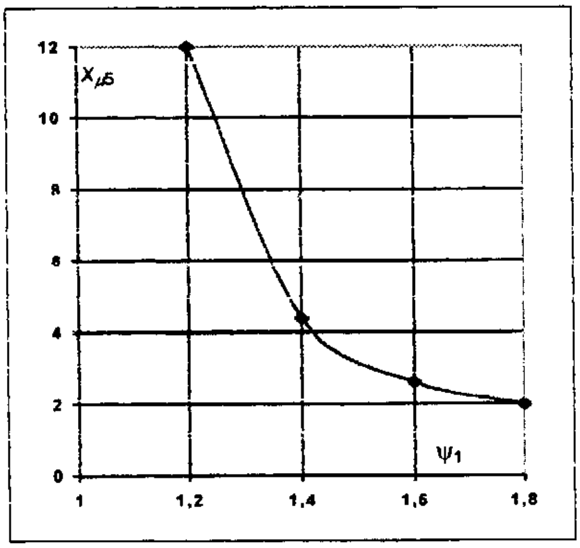

Fig. 7, *b* - Dependence of $x_{\mu 5}$ on ψ_1.

The most probable voltage increase is due to the 5th harmonic, which proves of practical importance when resonance is not present, too, or in case of inductive external impedance. For this last case, Eq. (4.3) leads to:

$$\underline{U}_{\mu k} = \underline{E}_{\mu k} \frac{x_{\mu k}}{x_{\mu k} + x_k}. \tag{4.4,a}$$

For line length between 300 km and 900 km (5th harmonic wave length from $\pi/2$ up to $3\pi/2$), the harmonic changes its sign at the line end, so it would be in phase with the fundamental component (see Fig. 7,*b*). The highest increase in voltage would evidently occur for lines of 600 km to 900 km, which show a capacitive line impedance /4, 5/.

CONCLUSIONS

Even for small deviations from balanced conditions at the fundamental frequency, it has been noted that harmonic unbalance can be significant. A model study of the different circuits including long lines reveals that most of the cases present voltage escalations dependent on the presence of the 5th, 7th, 2nd components or the presence of the f_s /3 sub-harmonic component. Transformer core saturation could - in certain cases – result in voltage escalations, as a result of the presence of high order and low order harmonic components, which could be of follow-up and resonance type.

In the case of 5th harmonic, it can be accepted that saturation and the non-linear element impedance are determined by the fundamental frequency flux, since the weigh of high order harmonics within the flux curve is low. The proposed procedure constitutes a variant of the harmonic analysis. *The method is used to study the 2nd and 5th harmonic components specific for the follow-up and resonant frequencies.*

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