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STUDY CASES REGARDING POWER LOSSES IN POWER SYSTEMS WITH POOR POWER QUALITY

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Abstract **– The assessment of power and energy losses in power systems is important for establishing networks characteristics and operating state, setting the electrical energy cost, estimating the efficiency of the losses reduction solutions etc. The power engineers need to know the power losses of each electrical element in order to design develop and operate the electrical power systems. Authors have developed a software product that calculates the power losses in electric lines and transformers in three-phase, three or/and four wires, under non-sinusoidal and unbalanced conditions. The paper presents the mathematical equations and the working methodology of this software tool. Some detailed examples are analyzed, comparing the results obtained for different operation modes: sinusoidal and balanced, non-sinusoidal and balanced, sinusoidal and unbalanced, non-sinusoidal and unbalanced.**

Keywords*: software product, electrical networks, power losses, harmonic pollution, unbalance*

1. INTRODUCTION

In the last three decades the concept of electric power quality has become frequently used. In a wide sense, power quality represents the electromagnetic disturbances influencing the electric power systems. Because of the negative impact of electromagnetic perturbations, particularly harmonics and unbalance, power engineers are very interested in these aspects of the electric power systems.
The existence of harmonics and unbalance in distribution and transmission electric networks leads to a particular operation regime. Mainly, this non-sinusoidal and unbalanced operation is caused by non-linear single-phase and three-phase asymmetric loads e.g. high-power electro thermal installations (mains frequency induction furnaces, welding transformers etc.), heating ventilation and air-conditioning (HVAC) systems, fluorescent lighting circuits with conventional and electronic ballast, computers for data processing and office automations etc. The disturbing consumer absorbs from the power supply more active and reactive power than it needs and puts out in the system a part of them as harmonic and unbalanced power.
Power losses in the generation, transmission and distribution systems occur during the process of consumers supplying. Depending on the structure of the power network, working conditions etc, the level of energy losses ranges between 10% and 15% of the energy produced by the power plants.[1] Harmonics and unbalance cause additional power and energy losses in all elements of the power system, with the following negative consequences: excessive heating of alternator rotors, saturation of transformers and ripple in rectifiers; sever instability problems of generators, additional power losses in neutral lines and also protection and interference problems, induced voltages in the neighboring communications circuits, gas pipelines and water pipelines etc.
It is necessary to estimate the power and energy losses for establishing the network characteristics and working state, setting the electrical energy cost, estimating the efficiency of the losses reduction solutions etc. Thus, power engineers need to know the power losses of each element in order to design develop and operate the electric power systems.
In spite of the above-mentioned aspects, the power designers calculate the power losses considering a sinusoidal balanced regime, and this approach can lead to undersizing of the network's elements, especially lines and cables. In the operation stage, it can generate many malfunctions or even failure of the entire power system.
To obtain truthful values of power losses, it is necessary to work with a great number of parameters that influence these power losses during a non-sinusoidal and unbalanced state. This is why the authors have developed an original software tool, called CPL (Computation of Power Losses), which performs the required complex mathematic calculations and quickly provides accurate results. In a few words, this software calculates the power losses in electric lines and transformers in three-phase, three or/and four wires, in non-sinusoidal and unbalanced conditions.
The paper presents the mathematical equations and a short description of the software tool and its working methodology (there is a wide description of CPL in [2]). Some detailed examples are analyzed, comparing the obtained results for different operation modes:

- sinusoidal and balanced;
- non-sinusoidal and balanced;
- sinusoidal and unbalanced;
- non-sinusoidal and unbalanced.

2. SOFTWARE TOOL

Software tool "Computation of Power Losses" contains two parts: the graphic user interface and the mathematical support.

2.1. Graphic User Interface

The graphic user interface (GUI) is the component of the software with which the user comes in contact. Through it, the user introduces the information needed to get the required results.
The GUI is composed of an entry window, a main window and several auxiliary windows.

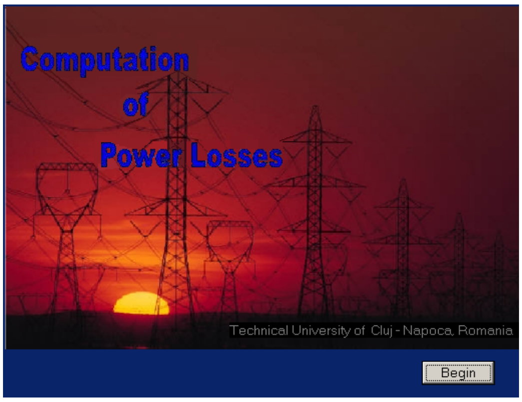

Figure 1: CPL's entry window

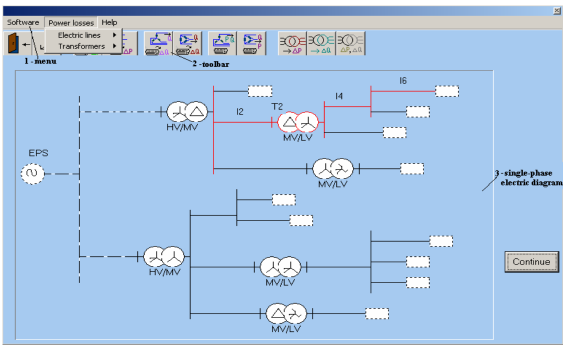

Figure 2: CPL's main window. 1 – Main menu, 2 – Buttons toolbar, 3 – Three-phase electric diagram

The entry window, presented in Fig. 1, is the first one that user sees when he opens the software. CPL's main window represents the start point of the power losses calculus, where the user chooses the way of introducing input data (using the main menu, toolbar or the electric diagram panel) and the type of losses that he needs (active or reactive) calculating.
The other auxiliary windows accomplish different tasks: give information about the program, acquire input data, present output data etc.

2.2. Mathematical support

The working methodology diagram of the software is illustrated in Fig. 3.

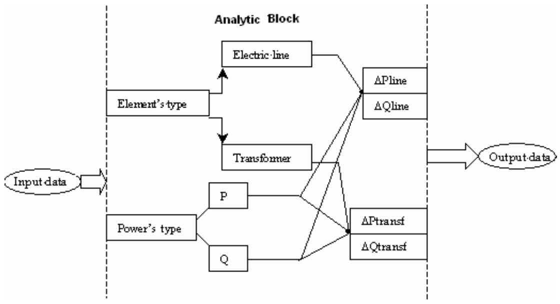

Figure 3: Software tool working methodology diagram

As it is explained in this image, input data are read, filtered and then used in the corresponding mathematical relationships for obtaining different kind of power losses: in electric lines/transformers, caused by the active/reactive power flow.
The analytic block includes the source code in which the mathematical relationships are implemented. To calculate the power losses in electric lines and transformers windings, the following relationships were used: [2]

a) Electric Lines:

- sinusoidal and balanced

$$\Delta P_L = 3 \cdot R_f \cdot I_1^2 \qquad (1)$$

- non-sinusoidal and balanced

$$\Delta P_L = 3 \cdot (\sum R_{fk} \cdot I_k^2), k = \overline{1, N} \qquad (2)$$

- sinusoidal and unbalanced

$$\Delta P_L = (I_A^2 + I_B^2 + I_C^2) \cdot R_f + I_N^2 \cdot R_N \qquad (3)$$

- non-sinusoidal and unbalanced

$$\Delta P_L = \Delta P_A + \Delta P_B + \Delta P_C + \Delta P_N \qquad (4)$$

b) Transformers:

- sinusoidal and balanced

$$\Delta P_T = \Delta P_{short-circuit} \qquad (5)$$

- non-sinusoidal and balanced

$$\Delta P_T = 3 \cdot \left(\sum R_{p,fk} \cdot I_{p,k}^2 + \sum R_{s,fk} \cdot I_{s,k}^2 \right), k = \overline{1, N} \qquad (6)$$

- sinusoidal and unbalanced

$$\Delta P_T = (I_{x,A}^2 + I_{x,B}^2 + I_{x,C}^2) \cdot R_x, x = p, s \qquad (7)$$

- non-sinusoidal and unbalanced

$$\Delta P_T = \Delta P_{p,x} + \Delta P_{s,x}, x = A, B, C \qquad (8)$$

where ΔP_L are the total active power losses in electric lines, ΔP_T – total active power losses in transformer windings, ΔP_i, ΔP_N – active power losses in line *i* *(i=A,B,C)* and neutral respectively, $\Delta P_{p,i}$, $P_{s,i}$ – active power losses in every transformer phase, on primary, and secondary windings respectively, $\Delta P_{,short\text{-}circuit}$ – nominal (tested) active power losses in transformer windings, R_{fk}, $R_{p,fk}$, $R_{s,fk}$ – line and transformer harmonic resistance respectively, $I_{i(N)}$ – line *i* and neutral RMS value of current respectively, I_1 – RMS value of the fundamental current, I_k – RMS value of range *k* harmonic current.

By reporting the total power losses obtained with relationships (4) and (8) to the power losses in sinusoidal and balanced regime, the additional power losses are obtained:

$$p = \frac{\Delta P_{Total} - \Delta P_{Ideal}}{\Delta P_{Ideal}} \cdot 100\,[\%]. \qquad (9)$$

where p are the additional power losses,

ΔP_{Total} - the total power losses calculated for a non-sinusoidal unbalanced operating state,

ΔP_{Ideal} - the power losses during a sinusoidal balanced regime.

3. STUDY CASES

The study cases illustrate how harmonic and unbalanced currents influence the power losses in a distribution network. The electric network presented in Fig. 3 has different operating states; in this case, ideal (sinusoidal balanced), non-sinusoidal balanced, sinusoidal unbalanced and real (non-sinusoidal unbalanced) stages were studied.

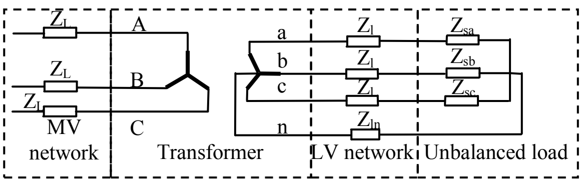

Figure 3: Distribution electric network

The values of network parameters do not modify during the operating state changing. The LV electric line has the following characteristics:

- cross-section $S_l = 25\,mm^2$,
- material Cu(copper),
- length $l = 500\,m$,
- reactance $x_0 = 0.086\,\Omega / km$.

The software calculates conductors' resistance considering the skin effect (resistance variation respect with the signal frequency).

Transformer characteristics are:

- rating $S_T = 160\,kVA$,
- primary line voltage $U_1 = 6\,kV$,
- secondary line voltage $U_2 = 0.4\,kV$,
- short-circuit voltage $u_{sc} = 6\,\%$,
- short-circuit power losses $p_{sc} = 3.26\,kW$,
- no-load power losses $p_0 = 0.86\,kW$,
- Yy_n connection.

The distribution network is supplying consumers of $S_S = 105\,kVA$ apparent power.

3.1. Ideal (sinusoidal balanced) operating state

During an ideal operating state the electric network is supplying balanced and linear loads. In this case the RMS values of the line currents are the same on every phase and there are no harmonic components. $I_a = I_b = I_c = 62\,A$.

The power losses caused by the active power flow are:

- $\Delta P_l = 4.11\,kW$, $p_l = 0.0\,\%$;
- $\Delta P_T = 0.91\,kW$, $p_T = 0.0\,\%$;

where ΔP_l are the total power losses in electric lines, ΔP_T - the total power losses in transformers, p_l and p_T - the supplementary power losses in electric lines and transformers, respectively.

During an ideal operating regime the additional power losses are zero.

3.2. Non-sinusoidal balanced operating state

The non-sinusoidal functioning regime of the electric network is the consequence of the non-linear loads (public lighting, electronic devices, induction furnaces etc). Thus the line currents are composed of the fundamental and the harmonic currents $\underline{I_a} = \sum_{k=1}^{N} \underline{I_{ak}}$, but their RMS values are equal on each phase:

- $I_{a1} = I_{b1} = I_{c1} = 62\,A$,
- $I_{a3} = I_{b3} = I_{c3} = 20\,A$,
- $I_{a5} = I_{b5} = I_{c5} = 4.6\,A$,
- $I_{a7} = I_{b7} = I_{c7} = 1.55\,A$,
- $I_{a9} = I_{b9} = I_{c9} = 0.4\,A$.

The power losses are:

$\Delta P_l = 4.75\,kW$, $p_l = 11.05\,\%$,

$\Delta P_T = 0.94\,kW$, $p_T = 2.82\,\%$.

In distribution networks that operate under harmonic and unbalanced conditions, due to the growing of the line currents, the power losses rise

3.3. Sinusoidal unbalanced operating state

The sinusoidal unbalanced operating regime is usually found in distribution networks that supply single phase loads (single phase resistive furnace for instance). These loads are unequal distributed on the three phases. The line currents contain only the fundamental component, but the current phasors system is unbalanced: the RMS values are different and the angle between phasors may differ from 120 electrical degrees; $\underline{I_a} = 45.65\angle 0°$, $\underline{I_b} = 85.1\angle 236°$ and $\underline{I_c} = 55.92\angle 127°$.

The power losses obtained are: $\Delta P_l = 4.84\ kW$, $p_l = 16.9\ \%$, $\Delta P_T = 0.95\ kW$, $p_T = 1.65\ \%$.

The unbalanced loads determine unbalanced currents that cause additional power losses in electric lines and transformers.

3.4. Real (non-sinusoidal unbalanced) operating state

In the present, due to the fact that the number of non-linear and single phase loads has grown, the real operating state of the distribution networks is non-sinusoidal and unbalanced. Thus, line current is different on each phase and it is composed of fundamental and harmonic currents; their values are:

- $I_{a1} = 39.84\angle 0.8°$, $I_{b1} = 85.58\angle 269°$, $I_{c1} = 61.13\angle 143°$;
- $I_{a3} = 8.13\angle 0.2°$, $I_{b3} = 27.07\angle 245°$, $I_{c3} = 27.17\angle 117°$;
- $I_{a5} = 1.62\angle 1.2°$, $I_{b5} = 6.3\angle 232°$, $I_{c5} = 6.11\angle 128°$;
- $I_{a7} = 0.61\angle 0.4°$, $I_{b7} = 2.7\angle 246°$, $I_{c7} = 1.35\angle 117°$;
- $I_{a9} = 0.2\angle 2.2°$, $I_{b9} = 0.45\angle 232°$, $I_{c9} = 0.67\angle 123°$.

In this case, the power losses are $\Delta P_l = 5.47\ kW$, $p_l = 32.1\ \%$, $\Delta P_T = 0.96\ kW$, $p_T = 5.93\ \%$.

Unfortunately, the real operating state of the distribution networks, i.e. non-sinusoidal and unbalanced, represents the worse case. As it can be seen, the power losses grow consistently and this fact negatively affects the elements of the power system.

4. CONCLUSIONS

Nowadays, the electric power systems supply a great variety of loads, most of them being single phase non-linear. Due to these loads the power system operates under non-sinusoidal and unbalanced conditions and the electrical components of the system are negatively affected. Among these negative effects, the growing of power losses is the worse. Today the power designers calculate the power losses considering a sinusoidal balanced regime. This fact can influence badly the electric networks because the additional power losses are not taking into account.

Considering the above mentioned facts, the authors have created a software tool for calculating the real power losses. By analyzing a distribution network supplying different consumers a comparison between the power losses under sinusoidal balanced and non-sinusoidal unbalanced conditions respectively is made. It can be seen that the power losses in electric lines grow with 32% and in transformers with 6%, values that this case should be taking in consideration.

Acknowledgments

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