THE INFLUENCE OF CONSIDERING THE LOAD-VOLTAGE CHARACTERISTICS ON THE ACTIVE POWER LOSSES

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Luarea în considerare a caracteristicilor statice de sarcină în funcţie de tensiune, în nodurile reţelei electrice şi pe ansamblul sistemului electroenergetic (SEN) are o influenţă directă asupra regimului de funcţionare, precum şi implicit asupra condiţiilor de optimizare a nivelului pierderilor de putere activă în reţelele electrice.

În cadrul lucrării se evidenţiază efectul considerării caracteristicilor statice de sarcină din nodurile reţelei electrice în alegerea regimului de tensiune pentru reducerea pierderilor de putere activă în reţelele de alimentare a utilizatorilor, oportunitatea aplicării acestei metode în optimizarea regimurilor de funcţionare a instalaţiilor electroenergetice (atât în proiectare cât şi în exploatare).

Considering the load-voltage characteristics according to voltage in the power network nodes and the whole national power system (NPS) has a direct influence on the operating condition and, implicitly, on the conditions to optimize the level of active power losses in the power networks.

The paper highlights the effect of considering the load-voltage characteristics within the power network nodes in choosing the voltage condition to reduce the active power losses in the power supply networks of the users, the opportunity of applying this method in optimizing the operating conditions of the power plants (both in design and operation).

Keywords: load characteristic, voltage control, active power losses in the power networks, power system, optimizing the operating condition

1. Introduction

Currently the European Union directs its attention to the problem of reducing the power losses in the power networks [1] [2] [3].

In Romania, there is a sustained concern for this purpose both in the design and procurement of equipment, for the new installations or upgrading, and - especially - in operation.

The studies in recent years have highlighted the importance of the correct regulation of voltage and reactive power so as to ensure the power efficiency programs in each area which are aimed at monitoring, best performance, increase

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of efficiency of electricity transmission process by reducing the active losses in the networks [4].

Currently, in Romania, in whole system there is a complete analysis and detailed statistical basis only for the transmission network (for the distribution network, the analysis is done on branches).

The sizing of the existing transmission network, primarily designed and built before 1989, considered the following:

a) a maximum power consumption of ~15000MW projected for the 1995 stage (the 1989 peak of consumption was ~12000MW) and a total installed power over 20000MW;
b) a flattened consumption curve;
c) a distribution of the power supply near the large users;
d) an operation of the power plants in the minimum fuel consumption criterion, taking account of consumption and the network losses (the relative consumption increase of each power plant was penalized by the effect on power losses in the system).

Under these conditions, in 1989 (the transmission and distribution networks having the same manager) the losses in Romania in the transmission and distribution network were 7.1% of the network input power. According to the data of the Statistical Yearbook for 2007, 11.03% was achieved - at the transmission operator (TO) and the distribution operator (DO) level.

The criterion for load distribution in the power plants participating in the electricity market is currently the one of the bids (order of merit) without having considered the optimization of the power system operation. The transmission system operator (TSO) has only the right / obligation to verify the conditions of safe operation of NPS [5].

2. Evolution of active power losses

The power losses are divided into:

- technical losses
- non-technical losses or commercial losses (thefts, meter losses, street lighting if it is not metered, measurement errors).

The technical losses in the power transmission are represented by the auxiliary technical consumption of the transmission network (**ATC**). The main types of active power losses are:

- Joule losses ($\Delta P=3RI^2$), produced by the transmission of the alternating current through the active conductors of the line, these power losses being transformed into heat;
- the corona losses due to the presence of the line electric field:

$\Delta P_{corona} = k(U - U_{cr})^2$, where U_{cr} the critical voltage where the corona discharge occurs, and k is a constant that depends on the relative air density, conductor surface condition, weather conditions, frequency etc.);

- the active power losses in no-load operation of the transforming units, approximately equal to the iron losses, $\Delta P_{FE} = \Delta P_{FE\_nom}(\frac{U}{U_{nom}})^2$ where there ΔP_{FE_nom} are the no-load losses measured at rated voltage;
- active power losses in the transformer dependent of its load, which are equal to the active power losses in windings, being proportional to the square of the load current:

$$\Delta P_T = \Delta P_k (\frac{S}{S_{nom}})^2 \tag{1}$$

Where:
ΔP_k are losses at rated load
S - transformer loading (MVA)
S_{nom} - rated power of transformer

- the active power losses in the shunt reactors which are determined by the magnetic core losses, proportional to $(\frac{U}{U_{nom}})^2$.

The losses arising in the operation of the power transmission network (**PTN**) are determined:

1. in the phase of the PTN development studies as a structure, for its consumption and distribution given by determining the justified level of economic losses (obviously they aren't the lowest);
2. in the design phase of PTN installations by establishing the technical parameters of the 400kV, 220kV transmission lines and the 400/110kV, 220/110kV and 400/220kV transforming units, in terms of no-load and load losses on established economic criteria.
3. in programming the installation operation analyzing:
   - ✓ premises in compliance with the sizing phase, determining the PTN structure under actual operating conditions (consumption, size and distribution sources in NPS);
   - ✓ need for additional installations to optimize the operating condition (including reactive power supplies, adjustment and control);

- ✓ need for measures in the operation of the existing installations (adapting the normal PTN operating diagram, programming the supply by taking into account the price of electricity).

4. real time operating by:
   - ✓ optimization - adapting the transmission operator's diagram
   - ✓ use of power supplies - within the limits allowed by the electricity market;
   - ✓ optimization of the voltage level and the reactive power flows.

The determination of network losses is achieved in relation to an **outline** of the installations. The transmission network in Romania (fig. 1) is considered as being consisted of the 400kV, 220kV installations, power lines and transforming units, the border between the 110kV terminals of the 220/110kV AT, 400/110kV TR respectively.

The accepted definition for the network losses with respect to the PTN outline is:

- the difference between the input energy of the PTN and the output energy of the PTN, including the consumption of the shunt reactors of the transmission installations, excluding the auxiliary consumptions of PTN installations taken by the transmission and distribution network (auxiliary services supplied by the tertiary of the transforming units and / or powered from EDN, losses in measurement installations, etc.) which are separately metered or assessed;
- as a percentage value relative to the electric energy in the outline.

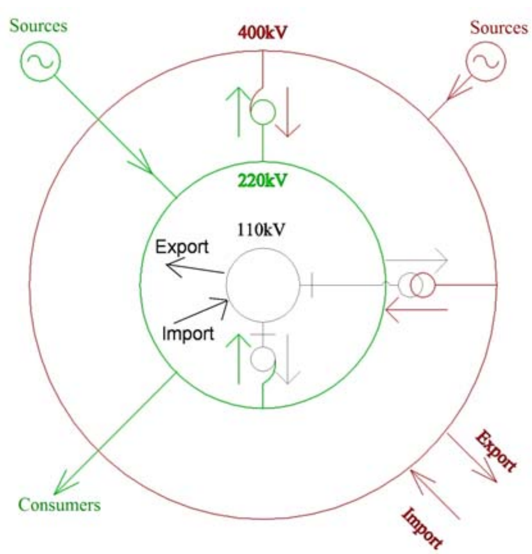

Fig. 1 Transmission network outline

Tables 1 and 2 present the evolution of the power/energy consumption, power/ energy production and the PTN losses during 2002-2010 in the transmission network.

Table 1

The evolution of the power/energy consumption and the power/energy production during 2002 - 2010 in the transmission network

Year	Net domestic consumption	Net peak power - consumption	Balance (exports - imports)	Net production	Net peak power - production	Balance at consumption peak
	(TWh)	(MW)	(TWh)	(TWh)	(MW)	(MW)
2002	47.524	7641	2.854	50.378	8326	685
2003	49.44	7542	2.085	51.525	7967	425
2004	50.745	8016	1.189	51.934	8496	480
2005	51.789	8102	2.915	54.804	9196	1094
2006	53	8151	4.2	57.4	8846	695
2007	54.15	8681	2.1	56.45	9285	604
2008	55.218	8589	4.433	59.77	9406	817
2009	50.64	8247	2.471	53.272	8825	578
2010	53.36	8464	2.919	56.546	9285	784

Table 2

Evolution of the PTN losses during 2002 - 2010 in the transmission network

Year	Losses (GWh)	Outline input energy (GWh)	Percentage of the outline input energy
2002	950.453	34807.64	2.731
2003	937.167	36.453.708	2.571
2004	957.222	36.469.090	2.625
2005	972.671	36.756.016	2.646
2006	989.747	40.788.874	2.427
2007	917.861	43.596.414	2.105
2008	997.576	45.485.370	2.193
2009	989.714	40.771.336	2.427
2010	1119.228	41605.3	2.69

Fig. 2 shows the evolution of the outline input power and Figs 3a and 3b the evolution of auxiliary technical consumption **(ATC)** (GWh and % of power) in phase 2002-2010.

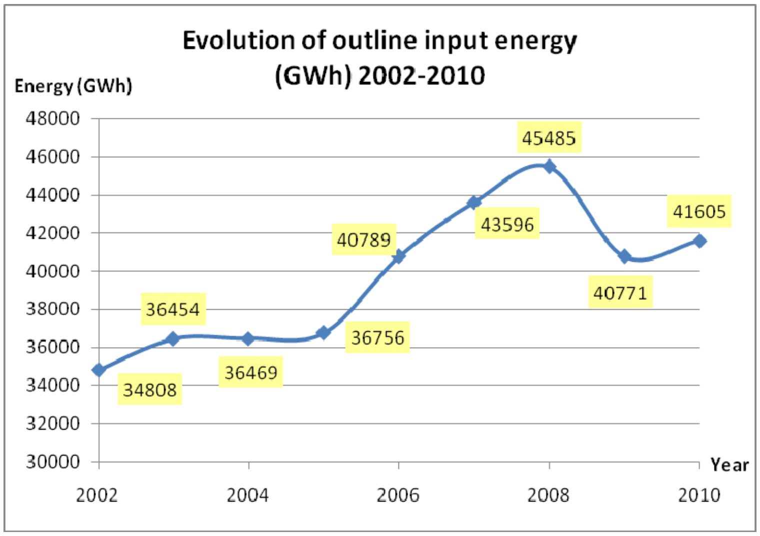

Fig. 2 Evolution of outline input energy

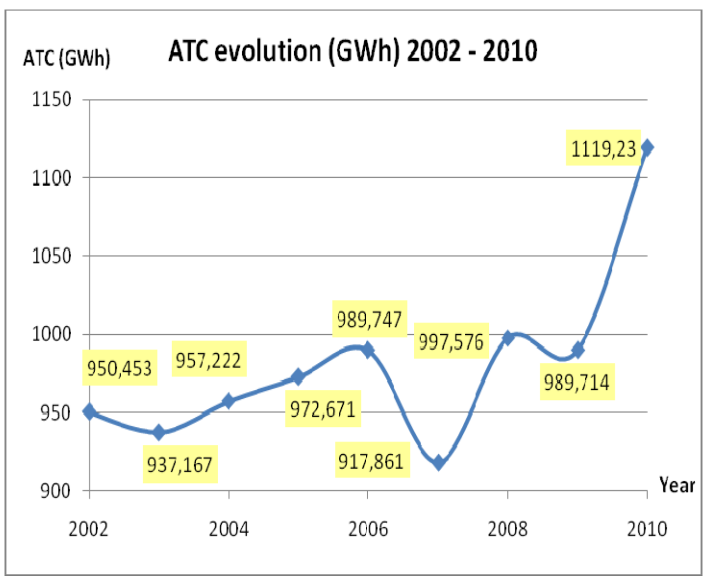

Fig. 3a ATC evolution

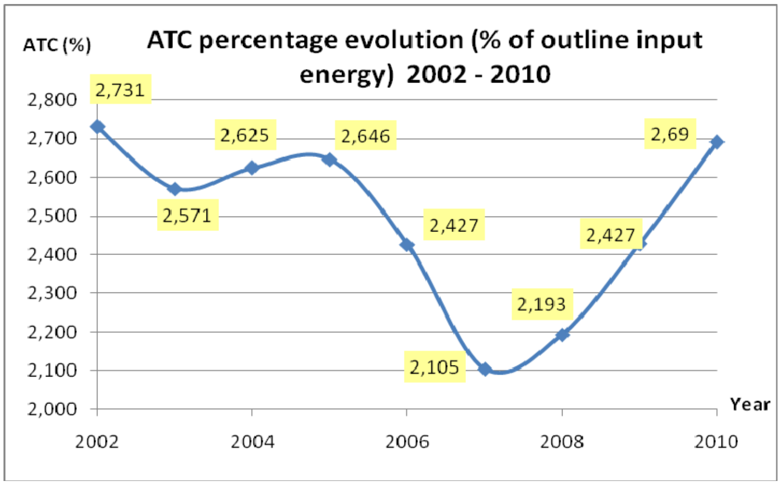

Fig. 3b ATC percentage evolution

The comparison of network losses between different countries and in the same country (system) in different periods is based on indicators reflecting the percentage of energy losses compared to the outline input energy.

The percentage values are determined by the relationship:

$$\Delta W\% = \frac{\Delta W}{W_S} \cdot 100 \tag{2}$$

where:

- ΔW - the energy losses obtained as the difference between the total outline input energy (W_S) and the outline output energy (W_i) - MWh;
- W_S is the amount of energy injected into the PTN outline: the energy received from the power plants connected to the 400kV and 220kV; the energy received from distribution network through the 400/110kV TR and the 220/110kV AT import, the energy of the 400kV and 110kV interconnection lines;
- W_i is the amount of the PTN outline output energy: energy supplied to consumers directly fed to 220kV; energy delivered to PTN by the 220/110kV AT and 400/110kV TR export, the output energy of the 400kV and 110kV interconnecting lines.

It is noted that although the active energy losses in absolute terms decreased in the period 2008 - 2009, the percentage losses increase marking a reduction of transmission networks efficiency.

Given the development of renewable sources, with a random operating condition, resulting in the need to develop transmission capacities with a limited number of production hours of use and which by their location in areas with low power consumption results in a significant increase in PTN losses, the need of considering the load-voltage characteristics will be even more important.

3. The influence of considering the load-voltage characteristics on the active power losses

The following will highlight the opportunities to reduce the PTN losses with respect to optimizing the voltage level considering the nodal characteristics P=f(U) and Q=g(U) [6].

The active power losses in power networks have the form:

$$\Delta P = R\frac{P^2 + Q^2}{U^2}, \tag{3}$$

have two components [7]:

- component due to active power flow:

$$\Delta P_P = R\frac{P^2}{U^2}; \tag{4}$$

- component due to reactive power flow:

$$\Delta P_Q = R\frac{Q^2}{U^2}. \tag{5}$$

The active and reactive power proportionally affects the active power losses.

Due to the complexity of final users receiving structure, the power transmission network nodes can be characterized by different load characteristics. Further analysis considers the specific load-voltage characteristics of major nodes in the power system. The adopted theoretical expressions simulate sufficiently the real characteristics, determined as a result of extensive experimental studies in the Romanian transmission system. In real cases, the system operators must determine, for each node, the mathematical model that defines best the consumption characteristics within the node.

1) For a voltage independent characteristic **P, Q = ct.:**

a) the active power losses vary with the ratio:

$$\frac{\Delta P_1}{\Delta P_N}=\frac{R\frac{P_1^2+Q_1^2}{U_1^2}}{R\frac{P_N^2+Q_N^2}{U_N^2}}=\frac{R\frac{2k^2}{U_1^2}}{R\frac{2k^2}{U_N^2}}=\frac{U_N^2}{U_1^2}=\left(\frac{U_N}{U_1}\right)^2; \quad (6)$$

b) the minimum losses are obtained at maximum voltage:

$$\Delta P_1=R\frac{2k^2}{U_1^2}; \quad (7)$$

2) For a characteristic ***P*, Q = k*U***:

a) the active power losses vary with the ratio:

$$\frac{\Delta P_1}{\Delta P_N}=\frac{R\frac{P_1^2+Q_1^2}{U_1^2}}{R\frac{P_N^2+Q_N^2}{U_N^2}}=\frac{R\frac{2k^2U_1^2}{U_1^2}}{R\frac{2k^2U_N^2}{U_N^2}}=1; \quad (8)$$

b) the minimum losses don't vary upon the voltage change:

$$\Delta P_1=R\frac{2k^2U_1^2}{U_1^2}=2Rk^2=ct.; \quad (9)$$

3) For a characteristic ***P*, *Q* = k*U*^{2}**:

a) the active power losses vary with the ratio:

$$\frac{\Delta P_1}{\Delta P_N}=\frac{R\frac{P_1^2+Q_1^2}{U_1^2}}{R\frac{P_N^2+Q_N^2}{U_N^2}}=\frac{R\frac{2k^2U_1^4}{U_1^2}}{R\frac{2k^2U_N^4}{U_N^2}}=\frac{U_1^2}{U_N^2}=\left(\frac{U_1}{U_N}\right)^2; \quad (10)$$

b) the minimum losses are obtained at minimum voltage:

$$\Delta P_1=R\frac{2k^2U_1^4}{U_1^2}=2Rk^2U_1^2; \quad (11)$$

4) For a characteristic ***P*, *Q* = k$_0$*U*^{2}+ k$_2$**:

a) the active power losses vary with the ratio:

$$\frac{\Delta P_1}{\Delta P_N}=\frac{R\frac{2\left(k_0U_1^2+k_2\right)^2}{U_1^2}}{R\frac{2\left(k_0U_N^2+k_2\right)^2}{U_N^2}}=\frac{\left(k_0^2U_1^4+2k_0k_2U_1^2+k_2^2\right)}{U_1^2}\cdot\frac{U_N^2}{\left(k_0^2U_N^4+2k_0k_2U_N^2+k_2^2\right)}=$$
$$=\frac{\left(k_0^2U_1^2+2k_0k_2+\frac{k_2^2}{U_1^2}\right)}{\left(k_0^2U_N^2+2k_0k_2+\frac{k_2^2}{U_N^2}\right)}; \qquad (12)$$

b) minimum losses:

$$\Delta P_1=R\frac{2\left(k_0U_1^2+k_2\right)^2}{U_1^2}=R\frac{2\left(k_0^2U_1^4+2k_0k_2U_1^2+k_2^2\right)}{U_1^2}; \qquad (13)$$

The function minimum value (13) is determined by the expression:

$$\frac{d\Delta P_1}{dU_1}=0; \qquad (14)$$

After the calculation, it will obtain the voltage value at which the minimum losses occur:

$$\rightarrow U_1=\sqrt[4]{\frac{k_2^2}{k_0^2}}=\sqrt{\frac{k_2}{k_0}} \text{ to which } k_0\neq 0 \text{ and } k_0,k_2>0 \text{ or } k_0,k_2<0$$

5) For a characteristic ***P, Q* = k$_1$*U*+ k$_2$**:

a) the active power losses vary with the ratio:

$$\frac{\Delta P_1}{\Delta P_N}=\frac{R\frac{2\left(k_1U_1+k_2\right)^2}{U_1^2}}{R\frac{2\left(k_1U_N+k_2\right)^2}{U_N^2}}=\frac{\left(k_1^2U_1^2+2k_1k_2U_1+k_2^2\right)}{U_1^2}\cdot\frac{U_N^2}{\left(k_1^2U_N^2+2k_1k_2U_N+k_2^2\right)}=$$
$$=\frac{k_1^2+\frac{2k_1k_2}{U_1}+\frac{k_2^2}{U_1^2}}{k_1^2+\frac{2k_1k_2}{U_N}+\frac{k_2^2}{U_N^2}} \qquad (15)$$

b) minimum losses result:

$$\Delta P_1 = R\frac{2\left(k_1U_1 + k_2\right)^2}{U_1^2} = R\frac{2\left(k_1^2U_1^2 + 2k_1k_2U_1 + k_2^2\right)}{U_1^2}; \tag{16}$$

Function (13) has a minimum value for

$$U_1 = \frac{k_2}{k_1}; \text{ to which } k_1 \neq 0 \text{ and } k_1, k_2 > 0 \text{ or } k_1, k_2 < 0 \qquad 17)$$

6) For a characteristic **P = k2 Q = k0*U*2**:

a) the active power losses vary with the ratio:

$$\frac{\Delta P_1}{\Delta P_N} = \frac{R\dfrac{k_2^2+k_0^2U_1^4}{U_1^2}}{R\dfrac{k_2^2+k_0^2U_N^4}{U_N^2}} = \frac{k_2^2+k_0^2U_1^4}{U_1^2}\cdot\frac{U_N^2}{k_2^2+k_0^2U_N^4} =$$

$$= \left(\frac{U_N}{U_1}\right)^2\cdot\frac{k_2^2+k_0^2U_1^4}{k_2^2+k_0^2U_{nom}^4} = \left(\frac{U_1}{U_N}\right)^2\cdot\frac{\dfrac{k_2^2}{U_1^4}+k_0^2}{\dfrac{k_2^2}{U_N^4}+k_0^2} \tag{18}$$

b) minimum losses result:

$$\Delta P_1 = R\frac{k_2^2+k_0^2U_1^4}{U_1^2}, \tag{19}$$

and the function minimum value is for the voltage

$$U_1 = \sqrt{\frac{k_2}{k_0}}, \text{ to which } k_0 \neq 0 \text{ and } k_0, k_2 > 0 \text{ or } k_0, k_2 < 0 \tag{20}$$

7) For a characteristic **P = k2, Q = k1*U***:

a) the active power losses vary with the ratio:

$$\frac{\Delta P_1}{\Delta P_N} = \frac{R\dfrac{k_2^2+k_1^2U_1^2}{U_1^2}}{R\dfrac{k_2^2+k_1^2U_N^2}{U_N^2}} = \left(\frac{U_N}{U_1}\right)^2\cdot\frac{k_2^2+k_1^2U_1^2}{k_2^2+k_1^2U_N^2} = \frac{\dfrac{k_2^2}{U_1^2}+k_1^2}{\dfrac{k_2^2}{U_N^2}+k_1^2} \tag{21}$$

For $U_1 > U_N \rightarrow \dfrac{\Delta P_1}{\Delta P_N} < 1 \rightarrow$ lower losses

For $U_1 < U_N \rightarrow \dfrac{\Delta P_1}{\Delta P_N} > 1 \rightarrow$ increased losses

b) minimum losses result:

$$\Delta P_1 = R\frac{\mathrm{k}_2^2 + \mathrm{k}_1^2 \mathrm{U}_1^2}{U_1^2}, \tag{22}$$

In this case, the minimum losses are obtained at maximum voltage

8) For a characteristic $\underline{\boldsymbol{P = \mathrm{k}_1 U \;\; Q = \mathrm{k}_0 U^2}}$:

a) the active power losses vary with the ratio:

$$\frac{\Delta P_1}{\Delta P_N} = \frac{R\dfrac{\mathrm{k}_1^2\mathrm{U}_1^2 + \mathrm{k}_0^2\mathrm{U}_1^4}{U_1^2}}{R\dfrac{\mathrm{k}_1^2\mathrm{U}_N^2 + \mathrm{k}_0^2\mathrm{U}_N^4}{U_N^2}} = \left(\frac{U_N}{U_1}\right)^2 \cdot \frac{\mathrm{k}_1^2\mathrm{U}_1^2 + \mathrm{k}_0^2\mathrm{U}_1^4}{\mathrm{k}_1^2\mathrm{U}_N^2 + \mathrm{k}_0^2\mathrm{U}_N^4} = \frac{\mathrm{k}_1^2 + \mathrm{k}_0^2\mathrm{U}_1^2}{\mathrm{k}_1^2 + \mathrm{k}_0^2\mathrm{U}_N^2}. \tag{23}$$

For $U_1 > U_N \rightarrow \dfrac{\Delta P_1}{\Delta P_N} > 1 \rightarrow$ increased losses

For $U_1 < U_N \rightarrow \dfrac{\Delta P_1}{\Delta P_N} < 1 \rightarrow$ lower losses

b) minimum losses result:

$$\Delta P_1 = R\frac{\mathrm{k}_1^2\mathrm{U}_1^2 + \mathrm{k}_0^2\mathrm{U}_1^4}{U_1^2}. \tag{24}$$

In this case, the minimum losses are obtained at minimum voltage.

The losses value can be optimized depending on load-voltage characteristics. It’s demonstrated that the minimum losses is possible to be obtained not only in maximum voltage (for non depending load type - constant power load) but also in minimum voltage (for constant impedance load).

On the basis of derived relations, a computer program (Fig. 4) that can take into account different types of node load-voltage characteristics within the power system and provide to the network operators the information necessary to operate, under the conditions of minimum active losses, was developed.

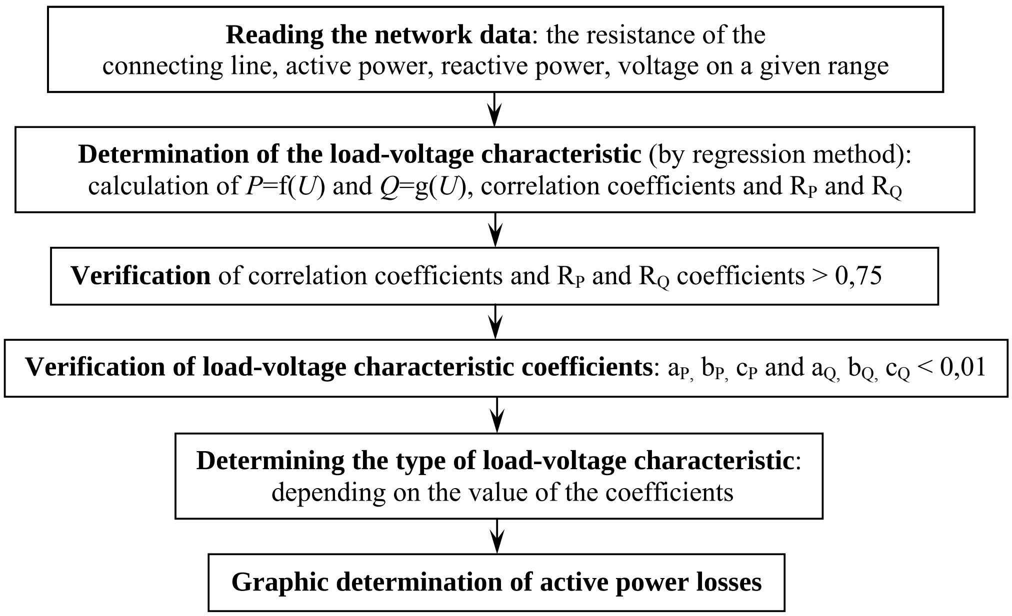

Fig. 4 Structural calculation diagram of the program for calculating the active power losses

The program developed in Matlab is proposed to be implemented in operative management system at transmission and distribution level. Also the dependencies obtained can be implemented in load flow calculations, with reference to those areas of consumption.

The program for calculating the active power losses depending on the load characteristic outlines the voltage level necessary to be maintained in a node to obtain minimal losses on that network.

Is proposed integration of the program in nodes (that supplies industrial users and / or household) established with the network operator to determine optimum operating voltage level.

The necessary data (active power, reactive power and voltage) are acquired through SCADA and telecommunication system existing on every network operator.

For example, Figs. 5a, 5b and 5c show the results for the theoretical case of some constant power type loads, constant current, constant impedance, respectively.

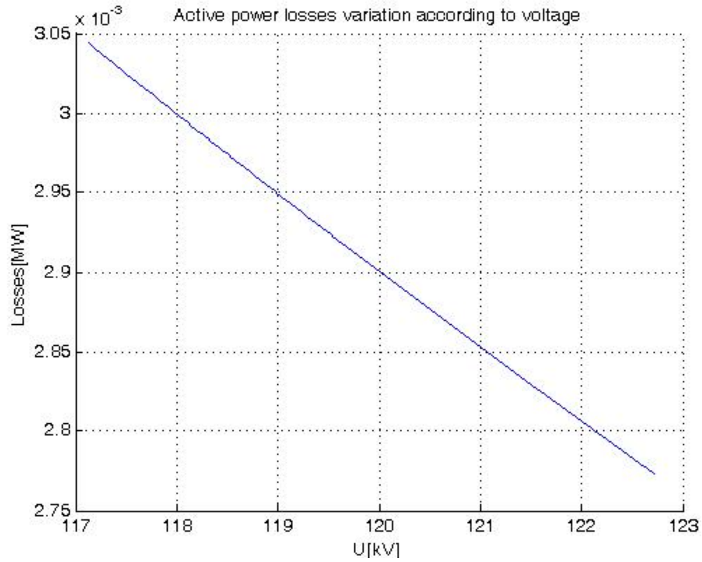

Fig. 5a Active power losses variation according to voltage value for a constant power load characteristic

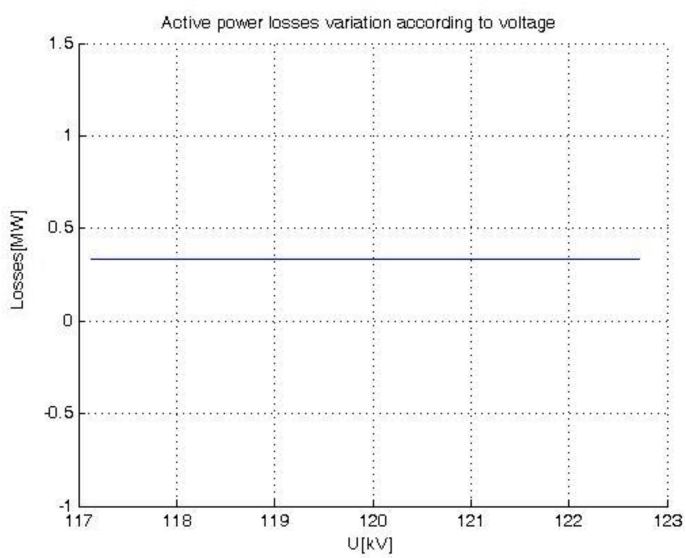

Fig. 5b Active power losses variation according to voltage value for a constant current load characteristic

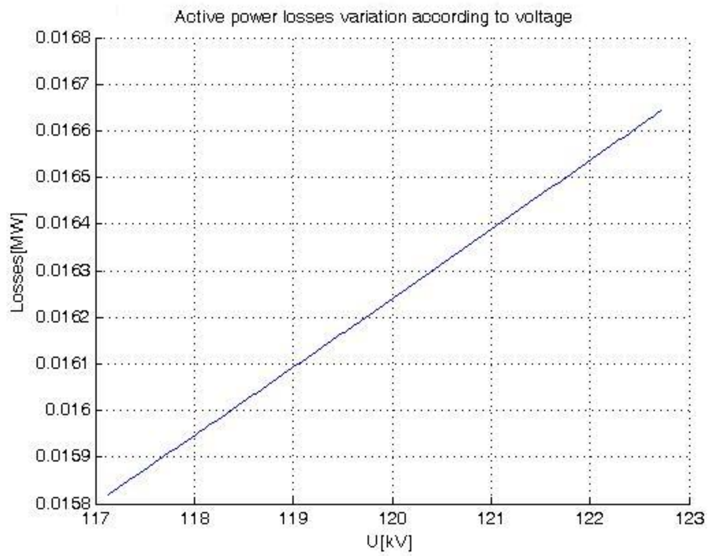

Fig. 5c Active power losses variation according to voltage value for a constant impedance load characteristic

It appears that if for a constant power type load, the minimum active power losses are obtained at maximum voltage, at a constant current type load, the active power losses remain constant regardless of voltage, and at the constant impedance type load, the minimum active power losses are obtained at minimum voltages.

The complexity of the power system processes makes the most reliable information on the load-voltage characteristics of nodes to be obtained by experimental measurements. Figs. 6a and 6b show experimental data obtained in two representative nodes of the Romanian power system.

- 1st representative node (fig. 6a):

$\boldsymbol{P}$=0,0791$\boldsymbol{U}^2$-19,2784$\boldsymbol{U}$ +1178,5887

$\boldsymbol{Q}$=-0,0381$\boldsymbol{U}^2$+9,3223$\boldsymbol{U}$ -572,1175

- 2nd representative node (fig. 6b):

$\boldsymbol{P}$=-0,0414$\boldsymbol{U}^2$+10,27$\boldsymbol{U}$ -631,7379

$\boldsymbol{Q}$=-0,0754$\boldsymbol{U}^2$+17,0735$\boldsymbol{U}$ -966,2357.

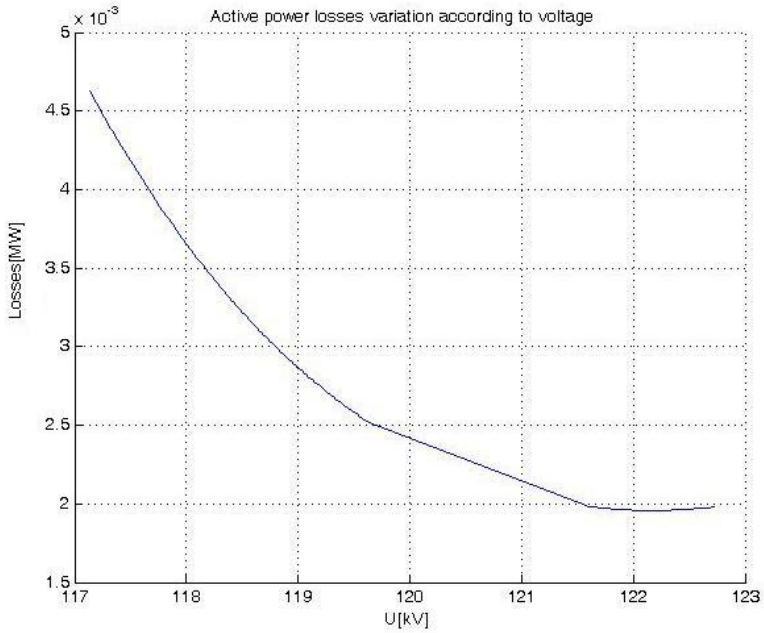

Fig. 6a Active power losses variation according to voltage value in the 1st representative node

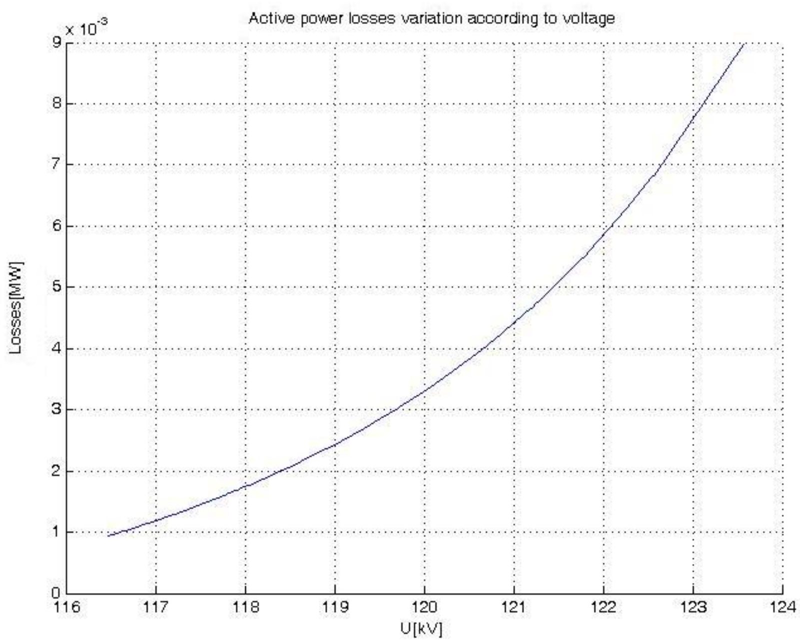

Fig. 6b Active power losses variation according to voltage value in the 2nd representative node

It is noted that the results obtained by the measurements made in the NPS led to the same conclusions: for measurements made in the 1st representative node, the minimum active power losses were obtained at maximum voltages, and for measurements made in the 2nd representative node, the minimum active power losses were obtained at minimum voltages.

4. Conclusions

This paper highlights the importance of knowing the load-voltage characteristic in determining the technological consumption (including the loss prospective studies) and the voltage level to be maintained in a consumption node to obtain minimum losses in the network (sometimes even minimum voltage).

For the calculation of active power losses (depending on the load characteristic) in the power supply network of some consumers, a dedicated algorithm and a computer program was used including both theoretical types of load-voltage characteristics and recorded power system data in two representative power supply nodes of some industrial consumers.

This program allows you to choose the optimal voltage level according to the load-voltage characteristic to reduce the active power losses.

It is proposed to integrate the program for determining the load-voltage characteristics and active power losses depending on the load characteristic in the representative system nodes, which supplies the industrial and / or household users, to determine the optimal operating voltage level.

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