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Estimation of Power/Energy Losses in Electric Distribution Systems based on an Efficient Method

G Grigoras*, V Alexandrescu, G Cartina, Fl Scarlatache
"Gheorghe Asachi" Technical University of Iasi, Faculty of Electrical Engineering, Iasi 700050, Romania
*Corresponding author, e-mail: ggrigor@ee.tuiasi.ro

Abstract

Estimation of the power/energy losses constitutes an important tool for an efficient planning and operation of electric distribution systems, especially in a free energy market environment. For further development of plans of energy loss reduction and for determination of the implementation priorities of different measures and investment projects, analysis of the nature and reasons of losses in the system and in its different parts is needed. In the paper, an efficient method concerning the power flow problem of medium voltage distribution networks, under condition of lack of information about the nodal loads, is presented. Using this method it can obtain the power/energy losses in power transformers and the lines. The test results, obtained for a 20kV real distribution network from Romania, confirmed the validity of the proposed method.

Keywords: *estimation, power/energy losses, electric distribution systems*

1. Introduction

Nowadays, power/energy saving has become a major problem in the worldwide. Numerous studies have indicated that reduction of power/energy losses in the electric networks is much easier than the increase of generating capacities, and energy efficiency represents the cheapest resource of all. But, determination of the power/energy losses depends upon a number of parameters and variables that derive from the design criteria and the operating conditions of the distribution networks. Thus, the feeders have a broad universe of the different variables, such as nominal voltage, the length, installed transformers capacity, the number of the transformation points, the circuit type (underground, aerial, mixed), load being served, etc [1-4]. Even if a feeder has more power losses compared with other feeders, it does not imply that it operates out of the normal condition. This may have more length, may be more loaded, and may have more transformation points, presenting different constructive or operative characteristics.

The problem of generating a coherent load set is critical in distribution, because usually, the only real time measurements available at a SCADA system are power or current values at the sending end of a feeder emerging from a HV/MV (high voltage/medium voltage) substation. One must therefore rely on other type of data, recorded in commercial files, to try inferring the values of load. A modern Demand Management System (DMS) must try to address the problem of evaluating actual synchronized flows and making this compatible with any measurements available at a SCADA system at any time. The complexity of the problem increased with the connection at distribution level [5-7]. On the other hand, in electrical distribution networks, except the usual measurements from HV/MV substations, there are few information about the state of network. As a result, there is at any moment a generalized uncertainty about the power demand conditions and therefore about the network loading, voltage level and power losses. The effects of the load uncertainties will propagate to the results, affecting the state estimation and the optimal solutions of the various problems concerning the minimization of energy losses [4], [7-9].

For further development of plans to reduce the power/energy loss and for determination of the implementation priorities of different measures and investment projects, an analysis of the nature and reasons of losses in the system and in its different parts must be done. A permanent policy for reduction of energy losses implies not only the technical improvement of the network (by introduction of modern equipments and circuit components), but also requires the use of software tools to facilitate the operation process [2], [5], [10].

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In this situation, different methods have been developed for solving the power flow problem. The classic methods of power flow calculation suppose that the load powers of the transformers are known [1-3], [8], [9], [11], [12]. But, in many electric substations, only the current injected into the distribution feeders is hourly measured and recorded. In the paper, using this information, and based on an efficient algorithm for to calculate the power flow of a distribution network, without information about the transformer loads, the power/energy losses were determined. The results obtained for different real distribution networks corresponding to a Distribution Company from Romania are in concordance with the real situation.

2. Algorithm for Power Flow Analysis in Electric Distribution Systems

The algorithm proposed for solving the power flow problem is referred to the networks with a tree-like structure supplied from the buses of medium voltage (MV) of the electric substations. One substation supplies one network, which contains more feeders.

For analysis of the network operation, the following hypotheses are taken into account: the power flow of the medium voltage lines is calculated separately of transformers; in consequence, the load currents must be considered on the medium voltage winding of transformers; in the algorithm frame there are procedures to create and manage the databases of lines and transformers with their technical data.

2.1. Structure Vectors

For fast recognition of network topology during the power flow calculations, the structure vectors are used [8]. Thus, the distribution lines are ordered, corresponding to the hierarchical ranks: 1, 2, and 3 as shown in Figure 1, so that it is possible to define two vectors of integer numbers (V_1 and V_2). If n_r is the number of the ranks and n_l is the number of the lines, then $dim(V_1)=n_r$ and $dim(V_2)=n_l$. The vector V_1 contains the number of lines in each rank in increasing order of ranks, and V_2 contains the line numbers in each rank in increasing order of ranks. For example, in case of the feeder from Figure 1, the structure vectors are given in Table 1.

Table 1. Structure Vectors

V_1	1	2		1
V_2	1	2	4	3

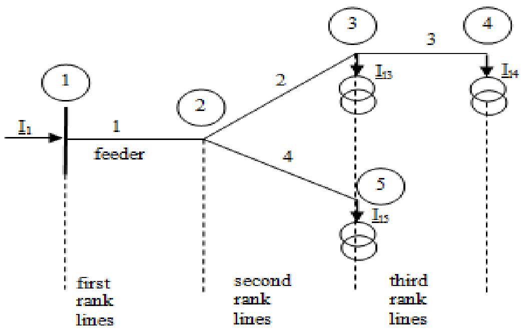

Figure 1. Example of a Distribution Feeder

In the algorithm frame, there are procedures to create and manage the databases of lines and transformers with their technical data. Also, for each feeder, the line and the node data are read and stored. The distribution lines and transformers are modeled by well known π and, respectively, Γ, single-phase equivalent circuits.

2.2. Power Flow Analysis of MV Networks

Under conditions specified above, the operation of the network, containing the lines only, with n nodes, can be analyzed by using the well known nodal equations in the matrix form, expressed in relation (1).

$$\left(\begin{bmatrix} \underline{Y}'_{11} & \underline{Y}_{12} & \cdots & \underline{Y}_{1n} \\ \underline{Y}_{21} & \underline{Y}'_{22} & \cdots & \underline{Y}_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \underline{Y}_{n1} & \underline{Y}_{n2} & \cdots & \underline{Y}'_{nn} \end{bmatrix} + \begin{bmatrix} \underline{Y}_{10} & 0 & \cdots & 0 \\ 0 & \underline{Y}_{20} & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & 0 & \underline{Y}_{n0} \end{bmatrix}\right) \begin{bmatrix} \underline{U}_1 \\ \underline{U}_2 \\ \vdots \\ \underline{U}_n \end{bmatrix} = \begin{bmatrix} \underline{I}_1 \\ -\underline{I}_2 \\ \vdots \\ -\underline{I}_n \end{bmatrix} \tag{1}$$

It is observed that the nodal admittance matrix in the left-hand side is decomposed in two matrices: one, written for longitudinal branches of π equivalent circuits only, being a singular matrix and the other is a diagonal matrix, written for the nodal capacitive admittances. The elements of the diagonal matrix are:

$$\underline{Y}_{i0} = \mathrm{j}\, b_{i0}\, \underline{U}_i,\ i = \overline{1,n} \tag{2}$$

Where b_{i0} is the capacitive susceptance connected at node i and $\underline{U}_i$, i=1, …, n are the nodal voltages. The equivalent circuit of whole feeder has n independent nodes. The nodal complex voltages can be written, point out to module and argument: $\underline{U}_i = U_i \cdot e^{j\theta i}$, i=1, …, n. For the source node $\underline{U}_1$ is fixed and chosen as phase origin, so that $\underline{U}_1 = U_1$. The flow chart of the proposed method is presented in Figure 2. The steps of algorithm are presented below.

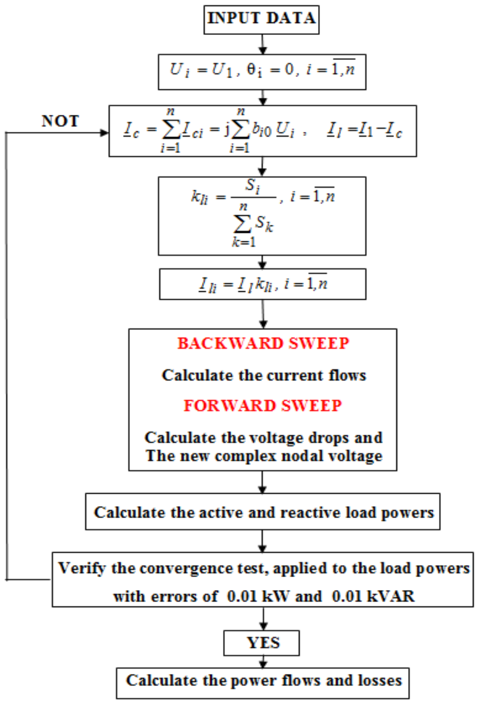

Figure 2. Flow-chart of the Proposed Method

The sum of all load currents, denoted by I_l is:

$$\underline{I}_l = \sum_{i=1}^{n} \underline{I}_{li} \tag{3}$$

Neglecting the conductance, the nodal capacitive admittances are:

$$\underline{Y}_{i0} = \mathrm{j}\, b_{io},\ i = \overline{1,n} \tag{4}$$

Where b_{i0} is the capacitive susceptance.
It results the expressions of nodal capacitive currents:

$$\underline{I}_{ci} = \mathrm{j}\, b_{i0}\, \underline{U}_i,\ i = \overline{1,n} \tag{5}$$

The balance of currents in the feeder is:

$$\underline{I}_1 = \sum_{i=1}^{n} \underline{I}_{ci} + \sum_{i=1}^{n} \underline{I}_{li} \quad (6)$$

So that, replacing the second sum by (3), the total load current results:

$$\underline{I}_l = \underline{I}_1 - \sum_{i=1}^{n} \underline{I}_{ci} \quad (7)$$

Considering that the transformers are loaded proportionally with their rated powers, the loading coefficients are:

$$k_{li} = \frac{S_i}{\sum_{k \in L} S_k}, i \in L \quad (8)$$

Where L is the set of load nodes. The complex load currents result:

$$\underline{I}_{li} = \underline{I}_l k_{li}, i = \overline{1,n} \quad (9)$$

To solve the power flow problem, the quantities: I_1, as module, U_1 and $cos\varphi$ are known, so that the active and reactive powers, injected into network from substation, can be easily calculated.

Using the above relations, the steps of the algorithm are:

1. Approximating the nodal voltages by real values equal to U_1;
2. Computing the capacitive currents with relation (5) and then, with (7), it results the total load current;
3. Computing the loading coefficients with relation (8) and then the nodal load currents with (9);
4. Using the structure vectors to:
   - calculate the current flows by backward sweep, beginning from the nodes of extremity to the supply node;
   - calculate the voltage drops and the new complex values of the nodal voltages by forward sweep, beginning from the supply node to the nodes of extremity;
4. By knowing the nodal load currents and the nodal voltages, the corresponding active and reactive load powers will be determined.
5. The usual convergence test is applied to the load powers: the calculation is convergent if, for all the load nodes, the absolute differences of active powers and, respectively, reactive powers from two consecutive iterations are less than the imposed errors. If the convergence is not verified, the calculation will be remade from step 2.
6. The power flow of the transformers. This calculus is made direct, without iterations, knowing the complex load current of primary winding of each transformer, the complex voltage applied at the sending end, the parameters of the Γ equivalent circuit, as well as the transformation ratios.
7. As final results, the following quantities are calculated: the nodal voltages and their arguments, active and reactive power flows in lines, active and reactive power losses and capacitive reactive power, provided from lines. For the transformers the following quantities are determined: the power losses, voltage drops, power demand at the receiving end and low voltage.

3. Evaluation of Energy Losses in Electric Distribution Systems

In the worldwide practice, in networks with high level of losses the metering system is usually poor measurements are fairly inaccurate or they are missing at all. It is obvious that due to poor provision with information such utilities have to apply simplified methods for calculation of technical losses basing primarily on energy metering. The energy data are sometimes partially supported by measurements of currents in outgoing medium-voltage feeders.

Thus, in the case when the active and reactive energies (W_P and W_Q), respectively the peak load current I_{max} of the feeder(s) are known, for energy losses can be used the following empirical formula:

$$\Delta W_{Total} = (\Delta P_L + \Delta P_{TrCo}) \cdot \tau + \Delta P_{TrIr} \cdot 8760 \quad (10)$$

Where: ΔP_L – the total active losses of the lines; ΔP_{TrCo} – the active losses in cooper wire; $\Delta P_{Tr\,Ir}$ – the active losses in iron; τ – loss factor.

Determination of loss factor can be done for each distribution feeder using the following formulae:

$$\tau = \left(0.124 + \frac{T_{max}}{10000}\right)^2 \cdot 8760 \,;\, T_{max} = \frac{\sqrt{W_P^2 + W_Q^2}}{S_{max}} \quad (11)$$

4. Case Study

Let consider an urban distribution network of with 50 feeders by 20 kV. The feeders are supplied from 8 110/20 kV electric substations. The characteristics of this urban distribution network are presented in the Tables 2 and 3.

Table 2. The Length of Cables in Function by Section for the Analyzed Distribution Network

Section [mm^2]	≤ 95	120	150	185	Total
Length [km]	18.23	41.43	152.77	74.30	286.73
Length [%]	6.36	14.45	53.28	25.91	100

Table 3. Distribution Transformer set for the Analyzed Distribution Network

Rated Power [kVA]	< 250	400	630	1000	1600	Total
No. of transformers [pcs]	78	204	154	69	13	518
Installed Power [kVA]	16569	81600	97020	69000	20800	284989

An analysis of the information contained in Table 2 indicates that the section by 150mm^2 predominates at the 20kV (≈50 % from total length of the network). Regarding the number of transformers, Table 3, it can observed that the average installed power of a transformer is about 550kVA, issue highlighted by the large number of the transformers with nominal power between 400 and 630kVA (≈ 70 % from total number).

In Figure 3 it presents a synthesis of the results obtained, by the calculation of annual energy losses using the algorithm described in the above paragraphs. The energy losses were calculated in percents from total energy flow in network. The results obtained by making the energy balance of 20kV feeders/electric stations are presented in the Table 4 and Figure 4.

The analysis of results allows us to draw the following conclusions: the majority of the 20 kV feeders have the energy losses below 5 %, higher values recorded are the few feeders; the annual total energy losses for the whole analyzed network are 3.26 %; no-loads losses from transformers have a high share in total energy losses (2.69 %), which mean that the network is low loading.

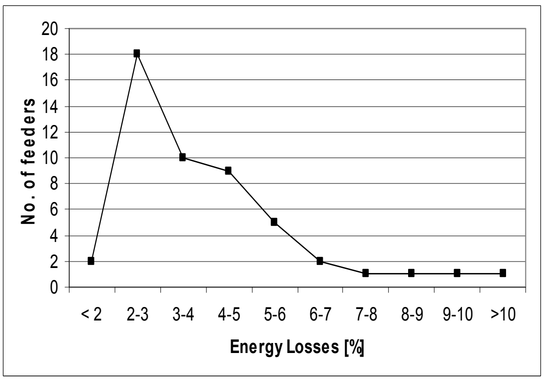

Figure 3. Distribution of the Annual Energy Losses by Number of Distribution Feeders

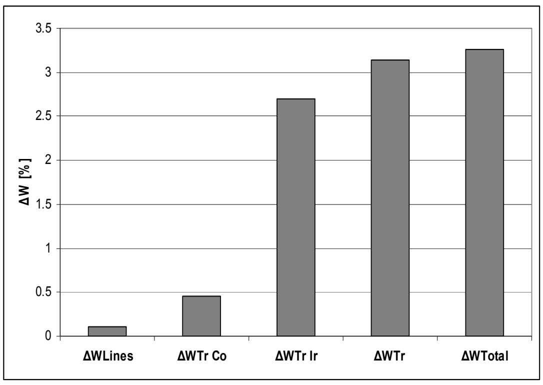

Figure 4. Annual Total Energy Losses for Analysed Distribution Network

Table 4. The Total Annual Energy Losses of Distribution Feeders/Electric Substations

No. Station	ΔW_L [MWh]	$\Delta W_{Tr\ Co}$ [MWh]	$\Delta W_{Tr\ Ir}$ [MWh]	ΔW_{Tr} [MWh]	ΔW_{Total} [MWh]	W_P [MWh]	ΔW_L [%]	ΔW_{TrCo} [%]	ΔW_{TrIr} [%]	ΔW_{Tr} [%]	ΔW_{Total} [%]
I	0.10	28.17	5.97	34.14	34.24	512.00	0.02	5.50	1.17	6.67	6.69
II	43.42	169.99	896.60	1066.59	1109.99	36929.00	0.12	0.46	2.43	2.89	3.01
III	44.75	157.40	691.44	848.84	893.59	37555.00	0.12	0.42	1.84	2.26	2.38
IV	31.49	88.02	618.50	706.53	738.02	20693.00	0.15	0.43	2.99	3.41	3.57
V	18.01	98.50	591.49	689.99	708.00	15761.00	0.11	0.62	3.75	4.38	4.49
VI	28.26	123.98	875.87	999.85	1028.11	32567.00	0.09	0.38	2.69	3.07	3.16
VII	1.38	16.99	315.47	332.46	333.84	4999.00	0.03	0.34	6.31	6.65	6.68
VIII	0.17	0.62	89.68	90.30	90.46	2630.00	0.06	0.02	3.41	3.43	3.44
Total	167.58	683.68	4085.02	4768.69	4936.24	151646.00	0.11	0.45	2.69	3.14	3.26

5. Conclusion

An efficient algorithm concerning the power flow problem of MV distribution networks, under condition of lack of information about the nodal loads, is presented. To solve the problem, it is absolutely necessary to approximate the loads by suitable methods. It is shown that the power flow analysis of the distribution feeders can be solved by separating the feeders in two parts, one of them using an iterative method and the other, containing transformers, by direct calculation. Thus, the power losses in the lines and power transformers are obtained. Further, based on these quantities, the annually energy losses can be calculated. The results obtained for a real distribution network from Romania, confirmed the validity of the proposed algorithm.

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