INCREASING THE ENERGY EFFICIENCY OF A POWER TRANSFORMATION AND DISTRIBUTION STATION

VERNICA SORIN-GABRIEL[1]*, GRIGORE ROXANA-MARGARETA[1], BANU IOAN-VIOREL[1], BARBU IOANA-MADALINA[1]

[1] "Vasile Alecsandri" University of Bacău, Faculty of Engineering, 157 Calea Mărășești, 600115 Bacău, Romania; sorin.vernica@ub.ro
* Correspondence: sorin.vernica@ub.ro

Received: 28.03.2025
Revised: 10.04.2025
Accepted: 02.09.2025
Published: 08.12.2025

Abstract: Substations are the main elements of an energy system that must ensure evacuation of power produced in the power plants, connection of lines to transit the power, distribution electricity to consumers. Reliability of a substation is essential for the role it plays in the energy system. In this paper are determined the energy losses in power lines and transformers associated with an electrical distribution station. The real operating regime is analyzed and an optimal model is established to improve the energy efficiency of the power station.

Keywords: substation, optimization, distribution, energy efficiency

1. INTRODUCTION

The efficient use of energy is a vitally important objective in the current stage of society's development. Precise knowledge of how energy is used in various categories of installations, as well as establishing the most efficient measures to reduce waste, can only be done based on an energy analysis.

In an electrical distribution station there are step-down transformers from 110 kV to medium voltage (20 or 6 kV). The largest electrical energy losses in the station occur in these transformers. That is why, in stations where there are two or more transformers operating in parallel, an optimal operating regime can be established for them, so that energy losses are minimal.

Reducing energy losses in electrical distribution and transformation stations has been extensively analyzed in the literature. For example, a study conducted in Nepal evaluates technical energy losses in 33 and 11 kV distribution networks [1]. Various reinforcement techniques are proposed, such as: upgrading conductors, placing capacitor banks and integrating photovoltaic panels. Another paper explores a comprehensive solution by using a dynamic voltage restorer connected with a Fuzzy logic controller [2]. This solution leads to the attenuation of voltage disturbances in the analyzed electrical networks. Additional research has been focused on ways to increase energy efficiency by modernizing existing power plants and lines and optimizing the locations where these improvements are made [3]. In the paper [4], several energy conservation options are analyzed, by using low-loss ferromagnetic core, by evaluating energy losses related to transformer power mismatch, low power factor and unbalance secondary load. Additional studies have evaluated optimization techniques by upgrading distribution transformers and positioning the tap changer for voltage regulation [5].

* Corresponding author, email: sorin.vernica@ub.ro https://doi.org/10.29081/jesr.v31i1.005

In this paper, an electrical distribution station is analyzed, with 2 transformers of 110/20 kV. An analysis of the real operating regime is carried out and then an optimal operating regime of the transformers is established so as to obtain an increase in the energy efficiency of the station.

2. DETERMINATION OF ENERGY LOSSES IN POWER LINES

Monthly energy losses in power lines are determined, [6], in the case of loading according to the load curve, with the following formula:

$$\Delta W_L = \Delta P_{dc} \cdot l \cdot T + r_0 \cdot l \cdot \frac{S_{max}^2}{U^2} \cdot \tau, \left[\frac{kWh}{month}\right] \tag{1}$$

where: ΔP_{dc} represents the specific power losses in the dielectric (in the case of underground power lines - UPL) or through the corona effect (in the case of overhead power lines - OPL), in kW/km, [8]; l – length of the power line, in km; T – duration of the characteristic regime, in h. The characteristic period is considered to be one month (T is the number of hours in that month); r_0 – specific resistance of the line, in Ω/km, [7, 9]; U – operating voltage in the characteristic regime, in kV; S_{max} – maximum apparent power calculated for the load curve of the characteristic regime, in kVA; τ – time of loss, in h, determined for the load curve of the characteristic regime.

According to [8], ANRE Order 75/2015, page 10, the losses through the corona effect are taken into account at 220 kV OPL - of 4-6 kW/km and at 400 kV - of 10-15 kW/km. In this case, $\Delta P_{dc} = 0$.

S_{max} is the maximum value of S recorded by the measuring devices. If only P and Q load curves are recorded, then S is calculated with the following formula and the maximum value is determined:

$$S = \sqrt{P^2 + Q^2}, [kVA], \tag{2}$$

$$S_{max} = \max(S), [kVA], \tag{3}$$

where: P – active power for the load curve of the characteristic regime, in kW; Q - reactive power for the load curve of the characteristic regime, in kVAr.

In this case, where the monthly average values of P and Q are given, determined from the monthly energies recorded by the meters, it is approximated:

$$P_{max} = 1.2 \cdot P; \;\; Q_{max} = 1.2 \cdot Q \tag{4}$$

and S_{max} is calculated with the formula:

$$S_{max} = \sqrt{P_{max}^2 + Q_{max}^2}, \tag{5}$$

τ – is determined with the following formula:

$$\tau = T \cdot \tau^* \tag{6}$$

where: τ^* - the loss factor, determined with the following relationship:

$$\tau^* = p \cdot k_u + (1 - p) \cdot k_u^2 \tag{7}$$

where: p – statistically determined coefficient having the value p ϵ (0.15÷0.3); in the absence of other information it can be considered p = 0,2, according to [6], page 11; k_u – the filling factor of the load curve, determined with the following formula:

$$k_u = \frac{S_{med}}{S_{max}} = \frac{T_{max}}{T} \tag{8}$$

$$S_{med} = \frac{\sqrt{W_a^2+W_r^2}}{T}, [kVA] \quad (9)$$

where: W_a , W_r – active, respectively reactive electrical energy transported through the power line during the characteristic regime T.

In this case, W_a, W_r are determined with relationships:

$$W_a = P \cdot T, \left[\frac{kWh}{month}\right]; \quad W_r = Q \cdot T, \left[\frac{kVAr}{month}\right] \quad (10)$$

where: T_{max} – duration of use of maximum apparent power, S_{max}, for the load curve of the characteristic regime, determined with the following formula:

$$T_{max} = \frac{\sqrt{W_a^2+W_r^2}}{S_{max}}, [h] \quad (11)$$

3. DETERMINATION OF ENERGY LOSSES IN TRANSFORMERS

Monthly energy losses in transformers are determined, [6], in the case of loading according to the load curve, with the following formula:

$$\Delta W_T = \Delta P_{fe} \cdot T + \Delta P_{cu} \cdot \frac{S_{max}^2}{U^2} \cdot \tau, \left[\frac{kWh}{month}\right], \quad (12)$$

where: ΔP_{fe} represents the no-load power loss of the transformer, in kW; ΔP_{cu} – power loss during short-circuit operation of the transformer, in kW; S_{max} - maximum apparent power calculated for the load curve of the characteristic regime, in kVA; U - operating voltage in the characteristic regime, in kV; τ - time of loss, in h, determined for the load curve of the characteristic regime.

S_{max} and τ are determined as in the case of line losses.

By summing the energies and losses from the 12 months, the balance for a year is obtained, in MWh/year.

The energy efficiency of the station is defined by the following indicators:

- net energy efficiency

$$\varepsilon_n = \frac{W_u}{W_i} \cdot 100, [\%] \quad (13)$$

- gross energy efficiency

$$\varepsilon_{br} = \frac{W_u+W_{SI}}{W_i} \cdot 100, [\%] \quad (14)$$

4. ESTABLISHING THE OPTIMAL OPERATING REGIME OF THE STATION

The characteristic part of establishing the optimal regime of a transformation station is the determination of the transformers that must operate and those that must be disconnected in various ranges of total apparent power required by the station, so as to achieve a minimum of power and active energy losses, but not only in the actual station considered, but in ensemble formed by this station and the networks that supply it, regardless of whether they belong to the station owner or to the energy system [11-13].

For this purpose, the load loss curves must be determined for all possible combinations of transformers and the number of transformers to cover the required load.

The active and reactive power losses on the set of *n* transformers operating in parallel are given by the following relations:

$$\Delta P_{tot} = \sum_{i=1}^{n} \Delta P_{fe_i} + \left(\frac{S}{\sum_{i=1}^{n} \frac{S_{n_i}}{u_{k_i}}} \right)^2 \cdot \sum_{i=1}^{n} \frac{\Delta P_{cu_i}}{u_{k_i}^2}, [kW] \tag{15}$$

$$\Delta Q_{tot} = \frac{1}{100} \cdot \sum_{i=1}^{n} \left(i_{0_i} \cdot S_{n_i} \right) + \frac{1}{100} \cdot \left(\frac{S}{\sum_{i=1}^{n} \frac{S_{n_i}}{u_{k_i}}} \right)^2 \cdot \sum_{i=1}^{n} \frac{S_{n_i}}{u_{k_i}}, [kVAr] \tag{16}$$

where: S – total apparent power required by the station, in kVA; S_{ni} – nominal apparent power of the transformer *i*, in kVA; i_{0i} – the no-load current of the transformer *i*, in percentage of the nominal current; u_{ki} – the short-circuit voltage of the transformer *i*, in percentage of nominal primary voltage.

Active power losses, ΔP_{ans}, on the entire station in *n* transformers operating in parallel and in the station's power supply networks – which are the losses that must be minimized – are given by the relationship:

$$\Delta P_{ans} = \Delta P_{tot} + \Delta P_{sist} + \Delta P_{Lac}, [kW] \tag{17}$$

in which: ΔP_{sist} – active power loss in the energy system networks, in kW, due to the transport, at the system's peak hour, of the reactive power ΔQ_{tot} lost in the *n* transformers:

$$\Delta P_{sist} = \Delta P_s \cdot \Delta Q_{tot}, [kW] \tag{18}$$

where: ΔP_s – specific active power loss in SEN networks due to the transport to the station of one kVAr at the system peak hour, depending on the system supply voltage of the station, according to Instruction E43-67, [10].

Is 0.025 at 110 kV; 0.03 at 25-60 kV, 6-20 kV coming directly from 110 kV or directly from the bars of a power plant; 0.045 at 6-20 kV coming from the double transformation of 110 kV and 0.06 at low voltage (LV).

We consider in this case the following value: $\Delta P_s = 0{,}03\ [kW/kVAr]$.

ΔP_{Lac} – active power loss in the consumer networks, through which the station is powered, due to the transport of reactive power ΔQ_{tot}:

$$\Delta P_{Lac} = R_r \cdot \left(\frac{\Delta Q_{tot}}{U} \right)^2, [kW] \tag{19}$$

where: R_r is the ohmic resistance – reduced to the primary voltage of the station – equivalent to the set of supply lines, from the system connection bars to the primary voltage bar on which the *n* transformers operating in parallel are connected:

$$R_r = RL \cdot \left(\frac{U}{U_r} \right)^2, [\Omega] \tag{20}$$

where: RL – effective ohmic resistance of the network considered, in Ω:

$$RL = r_s \cdot L, [\Omega] \tag{21}$$

r_s – specific resistance of the line, [7], [9], in Ω/km; U and U_r – the primary voltage of the considered station, respectively the voltage under which the considered network actually operates, in kV; L - length of the power line, in km.

In this case, $U = U_r$.

Based on the plotting of the curves, $\Delta P_{ans} = f(S)$, for all possible combinations of number of transformers and transformers connected operating in parallel, it is seen, for the various load ranges, which are the combinations that give minimum losses and the respective operating regime is adopted.

5. NUMERICAL RESULTS

As a numerical example, the analysis of the real operating regime of a 110/20 kV electrical substation is carried out, which has the simplified scheme in Figure 1.

There are 2 transformers in the station: one with a nominal apparent power S_{n1}=16 MVA and one with S_{n2}=25 MVA. The electrical power line, on 110 kV, OPL, consists of flexible uninsulated aluminum conductors steel reinforced (ACSR) of nominal cross-section 3*185 mm^2, length L=2 km.

The R1 transformer supply connection, at 110 kV, consists of flexible uninsulated ACSR with a nominal cross-section of 450/75 mm^2, length L_{t110}=0,007 km. The R2 transformer output connection, at 20 kV, is made of multi-wire aluminum cable, shielded, with polyethylene insulation type N2xS(FL)2Y, 3*1*150 mm^2, length L_{t20}=0,02 km.

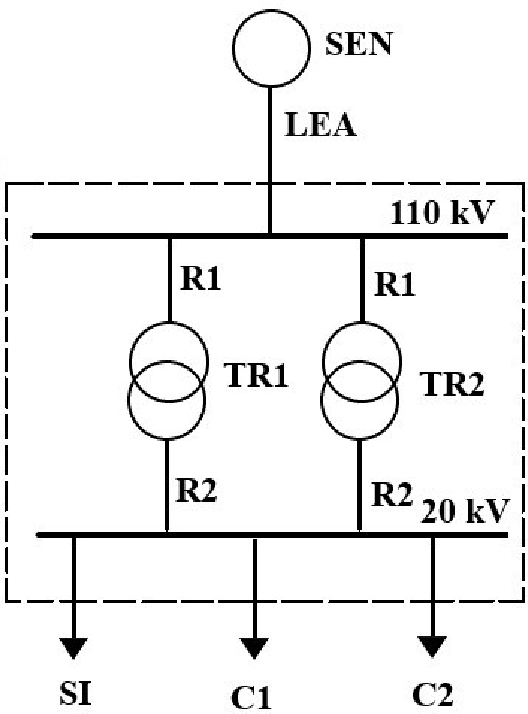
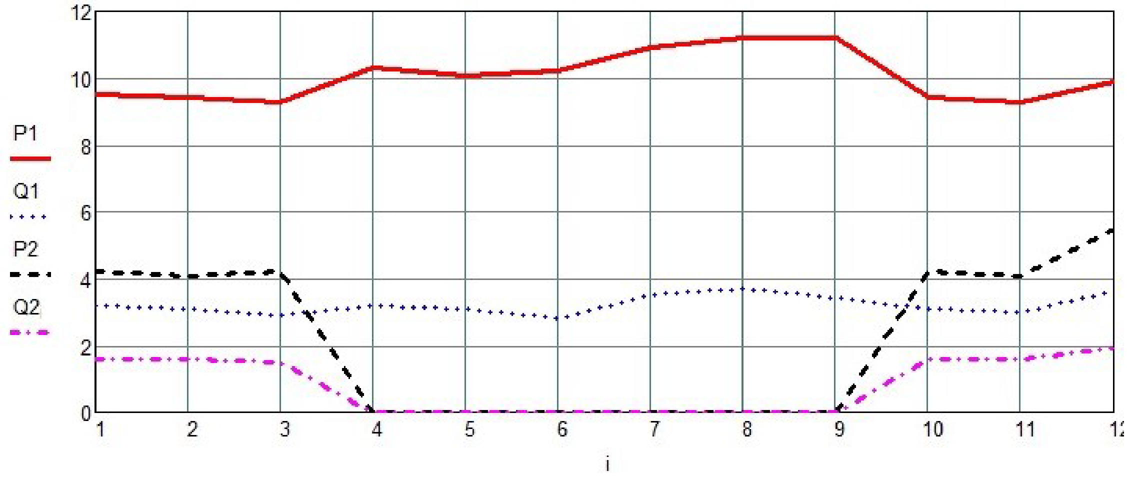
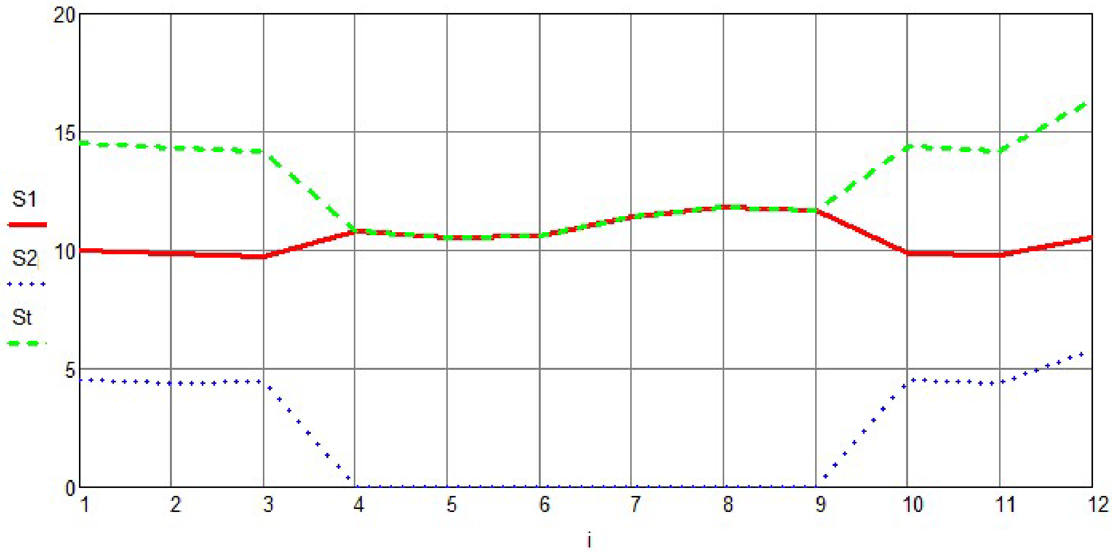


Fig. 1. Simplified scheme of the power station: SEN-national energy system; LEA-overhead power line; R1, R2-transformer connections; TR1, TR2-transformers; SI-internal services; C1, C2-consumers.

Figure 2 shows the active, reactive and apparent load curves for the two transformers. According to these curves, losses in lines and transformers are calculated. The results of the analysis of the real operating regime of the station are presented in Table 1.



a)



b)

Fig. 2. Load curves: a) – active power, P, in [MW], reactive power, Q, in [MVAr]; b) – apparent power, in [MVA]; Indices: 1, 2 – transformer 1, respectively 2; t - total; i=1…12 – the month number of the year

Table 1. Analysis of the real operating regime of the station.

Name	Symbol	Quantity	
		MWh/year	%
Useful	W_u	106488.083	99.231
Internal services	W_{SI}	64.388	0.06
Transformer 1 losses	ΔW_1	597.378	0.557
Transformer 2 losses	ΔW_2	152.025	0.142
Total transformer losses	ΔW_T	749.403	0.699
Transformer 1 connection losses	ΔW_{L1}	10.67	0.01
Transformer 2 connection losses	ΔW_{L2}	1.056	0.001
Total transformer connection losses	ΔW_L	11.726	0.011
Total losses	ΔW_G	761.129	0.709
Total out	W_e	107313.6	100

The net energy efficiency of the station is 99.23% and the gross energy efficiency is 99.29%.

Figure 3 shows the load loss curves, determined based on relations (16) and (17), for all possible combinations of transformers and the number of transformers to cover the required load.

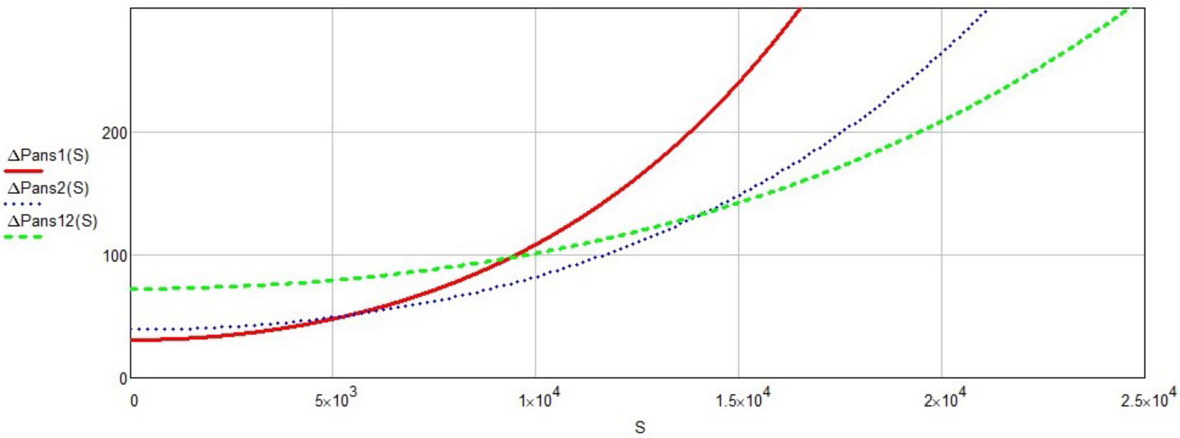


Fig. 3. The variation diagram of losses in the substation transformers, depending on the total load S, in [kVA]: ΔPans1(S), ΔPans2(S), ΔPans12(S) – active power losses in the case of operation of transformer 1, respectively 2 or of the two transformers in parallel, in [kW].

From the graph it can be seen that the lowest power losses are obtained for operation with:

- transformer 1 for total apparent power S_t<5373 kVA
- transformer 2 for 5373<S_t<14078 kVA
- transformer 1 + transformer 2 in parallel for St>14078 kVA

From the apparent power load curves, Fig.2.b), it is observed that the total apparent power S_t>5373 kVA all the time, so it will operate with:

- transformer 2 for S_t<14078 kVA
- transformer 1 + transformer 2 in parallel for S_t>14078 kVA

For this operating regime, energy losses in transformers and in conductors are calculated, Table 2.

Table 2. The optimal operating regime of the station.

Name	Symbol	Quantity	
		MWh/year	%
Useful	W_u	106711.649	99.439
Internal services	W_{SI}	64.388	0.06
Transformer 1 losses	ΔW1	235.911	0.22
Transformer 2 losses	ΔW2	296.35	0.276
Total transformer losses	ΔW_T	532.261	0.496
Transformer 1 connection losses	ΔWL1	3.614	0.003
Transformer 2 connection losses	ΔWL2	1.689	0.002
Total transformer connection losses	ΔW_L	5.303	0.005
Total losses	ΔW_G	537.563	0.501
Total out	W_e	107313.6	100

In the case of the optimized regime, the net energy efficiency of the station is 99.44% and the gross energy efficiency is 99.5%.

6. CONCLUSIONS

Providing consumers with energy at a high level of safety and quality, as well as the rational and efficient management of energy resources, requires, on the one hand, knowledge of the technical and economic performances of all the components of the energy chain and, on the other hand, ensuring their optimal operating conditions.

From Tables 1 and 2 it can be seen that by optimizing the operating regime of the transformers in the station, savings of 223 MWh/year are obtained, in the case of the analyzed station.

The largest share of savings is obtained in transformers, 97%. However, by optimizing the operation of transformers, energy savings of 2.8% are also achieved in the conductors.

REFERENCES

[1] Khatiwada, R., Bajracharya, T.R., Khan, S., Improving the energy efficiency of a power distribution network by loss reduction: A case study in rural 11 kV feeder, Journal of Advanced College of Engineering and Management, vol. 9, 2024, pp. 339-349.
[2] Shufian, A., Shib, S.K., Dipto, D.R., Rahman, M.T., Hannan, N., Fattah, S.A., Fuzzy logic-controlled three-phase dynamic voltage restorer for enhancing voltage stabilization and power quality, International Journal of Electrical Power and Energy Systems, vol. 166, 2025, art. no.110517.
[3] Halimjanova, M., Dettmann, K.D., Schulz, D., Kaatz, G., Grumm, F., Meyer, M.F., Ways to increase energy efficiency in the power system using the example of the Republic of Tajikistan, Ecosystems and Sustainable Development, WIT Transactions on Ecology and the Environment, vol. 4, 2017, pp. 57-65.
[4] Mandi, R.P., Enhancing energy efficiency of distribution transformers through energy conservation techniques, International Research Journal of Power and Energy Engineering, vol. 3, no. 2, 2017, pp. 104-111.
[5] Okorie, N.S., Idoniboyeobu, D.C., Braide, S.L., Optimization of energy efficiency for electric power distribution system losses, International Journal for Research in Applied Science and Engineering Technology, vol. 9, no. XII, 2021, pp. 934-940.
[6] ***NTE 013/16/00 – Normă tehnică energetică privind determinarea consumului propriu tehnologic în rețelele electrice de interes public.
[7] ***PE134-95 – Normativ privind metodologia de calcul a curenților de scurtcircuit în rețelele electrice cu tensiuni peste 1 kV.
[8] ***Ordin ANRE 75/2015 pentru aprobarea Procedurii privind corecția datelor de măsurare în raport cu punctul de delimitare.
[9] ***NTE 007/08/00 – Normativ pentru proiectarea și executarea rețelelor de cabluri electrice.
[10] ***E43-67 Instrucțiune privind ameliorarea factorului de putere la consumatorii industriali și similari de energie electrică.
[11] Hazi, A., Hazi, Gh., Bilanturi energetice. Teorie si aplicaţii, Editura Pim Iasi, 2020.
[12] Vernica, S.G., Eficienta energetica. Aplicatii, Editura Alma Mater Bacau, 2024.
[13] *** PE 902/1986 – Normativ privind intocmirea si analiza bilanturilor energetice.