STABILIZING THE OPTIMAL OPERATION STATES OF TRANSFORMER STATIONS FOR SUPPLYING THE INDUSTRIAL CONSUMERS WITH ELECTRIC ENERGY

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1. Introduction

The preoccupation viewing the optimization of transformer's nominal power and of transformer stations configuration from the industrial consumers, are justified by important obtainable energy savings. In this sense, the satisfying results offers the application of the criterion of applying the criterion [1,2,5,6] of "minimal power and energy losses", but for obtaining of some more exactly values there is applied the criterion of "total updated costs". In this paper there are analyzed the"2 x 100%" configurations typical to MV/LV stations of industrial consumers [1,4,6,8].

In fig.1, is presented the frequently applied scheme. To make the analyzing there are allowed the following hypothesis: the nominal power of the transformer is the most optimal, the characteristics of the same type devices are same and the momentary input power (S) is variable (for a working day). In fig. 1 are introduced the following notations: C_1, C_2 – MV cells, T_1, T_2 – transformers of MV / LV, C1', C2' – the cells of LV. The switching equipment may be having ASR – automat switching on system of the reserve.

There is noted with:

1. the state with a single supplying path in operation (with passive reserve)
2. the state with two paths of supplying in operation (active reserve).

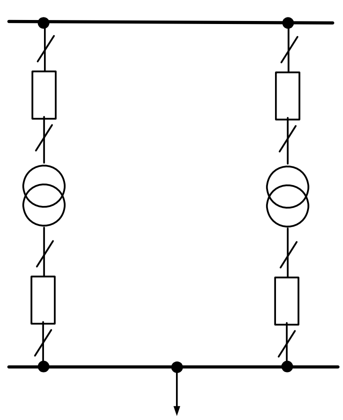


Fig. 1 – Scheme of 2 x 100% configuration type

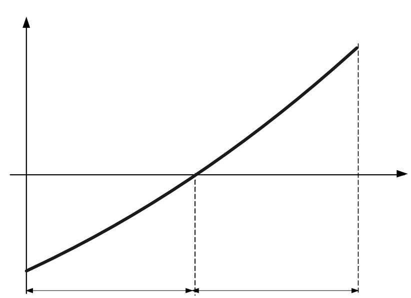


Fig. 2 – Variation of the power losses in function with the input power

There will be given the calculation relations for the input power at which is imposed the switching between two states, in relation with the applied optimization criterion and factors of consideration influence.

2. Application of the criterion "minimal losses of power"

If there is noted with $\Delta P_{12} = \Delta P_1 - \Delta P_2$ the difference of the total power in transformers, referring on the two sates, results:

- neglecting the reactive power losses:

$$\Delta P_{12} = \frac{\Delta P_w}{2}\left(\frac{S}{S_n}\right)^2 - \Delta P_F\,; \qquad S_e = S_n\sqrt{\frac{2\cdot\Delta P_F}{\Delta P_w}} \tag{1}$$

- taking into account the reactive power losses:

$$\Delta P_{12} = \frac{1}{2}\left(\Delta P_w + \lambda\frac{U_{sc}}{100}S_n\right)\left(\frac{S}{S_n}\right)^2 - \left(\Delta P_F + \lambda\frac{I_0}{100}S_n\right);$$
$$S_{e\lambda} = S_n\sqrt{\frac{2\left(\Delta P_F + \lambda\frac{I_0}{100}S_n\right)}{\Delta P_w + \lambda\frac{U_{sc}}{100}S_n}} \tag{2}$$

where:

$\Delta P_W, \Delta P_F$ - are the nominal losses in windings and iron circuit of the transformer [kW];
S_n, S_e, $S_{e\lambda}$ - nominal power of a transformer (S_n) and the input powers at which is assessed the switching between the two states; (fig. 2)
I_0, U_{sc} – non-load current and short circuit voltage (the nominal values) of the transformer [%];
λ - energy equivalent of reactive power [kW / kVAr].

3. Application of "total updated costs" (TUC) criterion with considering the factors: proper technological consume (PTC) and safety level (SL)

The expression of TUC alternates between the two states is:

$$TUC_{12} = TUC_1 - TUC_2 = \sum_{t=0}^{T'}\left(\Delta C_{12t}^E + \Delta D_{12t}\right)(1+a)^{-t} \tag{3}$$

where:
t, T' – the current year (t) and the study period (T)
a – updating rate

The variation of electric energy costs is determinate with the following relation:

$$\Delta C_{12t}^E = C_{1t}^E - C_{2t}^E = \Delta P_{12}\cdot\overline{K}_{Et}\cdot\tau \tag{4}$$

where:
$\overline{K}_{Et}$ - is the average cost of electric energy in "t" year [MU/kWh]
τ - time to failure of the installation, in the given configuration in "t" year [h]
MU – monetary unit

To evaluate the supplementary damage by the analyzed consumers in state 1 in relation with state 2, in “t” year, we propose to apply the following expression [7]:

$$\Delta D_{12t} = D_{1t} - D_{2t} = \Delta\nu_{Tt}^{12} \cdot D_0 + \sum_{i\in t;T_{CR_i}<t_{CRZ}}^{T_{d_i}\geq T_{d_m}} \Delta n_{di}^{12} \cdot D_{ndi} + \beta_t \cdot D_d \qquad (5)$$

$$\beta_t = \begin{cases} \Delta\nu_t^{12} \cdot t_{CRZ}\ ;\text{for } r_{CRZ} \leq T_{dM} \\ \beta_t^1;\ \text{for } t_{CRZ} > T_{dM} \end{cases} \qquad (6)$$

where:

$\Delta\nu_t^{12}$ - is the probably increasing of the total number of failures, on LV bar, in state 1 in relation with state 2 in “t” year;

Δn_{di}^{12} - number of probably failures with a certain duration (T_{di}) lest equal with the significant minimal value (T_{dm}) in year “t”, for state 1 in relation with state 2;

t_{CRZ} – time interval for switching to reserve supplying [h];

T_{dM} – maximal probable duration of the basic supply [h].

β_t^1 - probable time interval where the basic supply is in fault in “t” year [h];

D_0 – probably damage in moment of the interruption (T_{CR}) [MU];

D_{ndi} – probable damages at different critical moments of the interruption (T_{CR0}; $i \geq 1$) [MU];

D_d – the probable damage depending on the interruption’s duration [MU/h].

The number of the double faults is negligible, in comparison with the simple one, it may be written:

$$\Delta\nu_t^{12} = \nu_t^1;\ \Delta n_{di}^{12} = n_{di}^1;\ T_{di}^{12} = T_{di}^1 = T_{di} \qquad (7)$$

where:

T_{di}^{12} - is the duration of interruption in state 1 in relation with state 2;

ν_t^1, n_{di}^1, T_{di}^1 - have the same significance with indices $\Delta\nu_{Tt}^{12}, \Delta n_{di}^{12}, \text{and}\ T_{di}^{12}$, referring on only state 1;

The mentioned indices are determinate for an element (e_j) with relation [3]:

$$n_{dj} = \frac{\lambda_j \cdot \mu_j}{\lambda_j + \mu_j} T_A;\ T_{dj} = \frac{1}{\mu_j} \qquad (8)$$

where:

λ_j, μ_j – are the intensities of faulty and repair [h^{-1}];

T_A – the period of analyze [h].

After evaluating of the doublets $(n_{dj}, T_{dj})_j = \{C, T, C^i\}$ are determined the following indices:

$$\nu_t^1 = n_{dc} + n_t + n_{dc'};\quad \beta_t^1 = n_{dc} \cdot T_{dc} + n_t \cdot T_t + n_{c'} \cdot T_{dc'} \qquad (9)$$

The categories of damages D_0, D_{ndi}, D_d will be determined in function with the specifically indices of the damage with relation [3,7]:

$$D_0 = P_0 \cdot d_{p0}$$
$$D_{ndi} = P_{nd} \times d_{Pi} \qquad (10)$$
$$D_d = K_u \cdot P_d \cdot d_w$$

where:

d_{P0}, d_{Pi} – represents the relative damage of the installed capacity, corresponding receptor groups at which exists T_{CR0} (d_{P0}) and T_{CRi} (d_{Pi}) i ≥ 1) [MU/kW];
d_w – relative damage at undelivered energy [MU/kW];
P_0, P_{nd}, P_d – the installed capacities in receptor groups for which are presented the categories of D_0, D_{ndi}, D_d of the damage [kW];
K_u – the utilizing coefficient of the input power, by the group of receptors.

There is considered, that it is more useful if relation (3) is applied for "t" year when the analyze is made. In this case, the power at which is made the switching between the two states, results from the relation:

$$\frac{1}{2}\left(\Delta P_W + \lambda \frac{U_{SC}}{100} S_n\right)\left(\frac{S}{S_n}\right)^2 \cdot \overline{K}_{Et} \cdot \tau - \left(\Delta P_F + \lambda \frac{I_0}{100} S_n\right) \cdot \overline{K}_{Et} \cdot \tau + \Delta D_{12t} = 0 \qquad (11)$$

The expression of the power will be:

$$S_{e\lambda D} = S_n \sqrt{\frac{2\left(\Delta P_F + \lambda \frac{I_0}{100} S_n\right) \cdot \overline{K}_{Et} \cdot \tau - 2\Delta D_{12t}}{\left(\Delta P_W + \lambda \frac{U_{SC}}{100} S_n\right) \cdot \overline{K}_{Et} \cdot \tau}} \qquad (12)$$

4. Application of the criteria TUC with all factors considering

The expression of TUC variation, referring on the two states for "t" year is:

$$TUC_{12} = \frac{1}{2}\left(\Delta P_W + \lambda \frac{U_{Sc}}{100} S_n\right)\left(\frac{S}{S_n}\right)^2 \cdot \overline{K}_{Et} \cdot \tau - \left(\Delta P_{Fe} + \lambda \frac{I_0}{100} S_n\right) \cdot \overline{K}_{Et} \cdot \tau + \Delta D_{12t} + \Delta C_{12t} + \Delta I_{12t} \qquad (13)$$

That involves the power computing at which is justified the switching between the states, basing on the expression:

$$S_{e\lambda D}^{CI} = S_n \sqrt{\frac{2\left(\Delta P_F + \lambda \frac{I_0}{100} S_n\right) \cdot \overline{K}_{Et} \cdot \tau - 2(\Delta D_{12t} + \Delta I_{12t} + \Delta C_{12t})}{\left(\Delta P_W + \lambda \frac{U_{SC}}{100} S_n\right) \cdot \overline{K}_{Et} \cdot \tau}} \qquad (14)$$

where:

ΔC_{12t} - supplementary costs in "t" year, through the operating, state 1 or 2 in relation with the permanently operating in state 2 [MU];
ΔI_{12t} - quota of invested supplementary costs, that corresponds to "t" year for the period of study, due to the alternative operating in state 1 or 2, in function with permanently operation in state 2 [MU].

The costs ΔC_{12t} especially refers on, the values of the elements in the interruption, that are supposed on the accelerated usage, by repeated maneuvers, that must be supplemented with the revision that may be appreciated with the relation:

$$\Delta C_{12t} = \Delta N_{12t}\left(\frac{C_t}{N_R} + \frac{C'_t}{N'_R}\right) = (N_{1t} - N_{2t})\left(\frac{C_t}{N_R} + \frac{C'_t}{N'_R}\right) \tag{15}$$

where:

N_{1t}, N_{2t} – number of the maneuvers at which are supposed the switchers in case of alternating operation 1-2(N_{1t}) respectively, stabile operation in state 2(N_{2t}).
N_R N'_R – number of the maneuvers between two consecutively revision of the switcher MV(N_R) and LV(N'_R).
C_t, C'_t – annual exploitation costs (exclusively pay and PTC) afferent to a switcher of MV(C_t) and LV(C'_t) [MU].

To evaluate the term of ΔI_{12t} may be applied the relation of:

$$\Delta I_{12t} = \frac{V_{AC}^{ti} - W_{AC}^{ti}}{(t_i - t)(1+a)^{ti-t}}; \quad t_i > t \tag{16}$$

where:
V_{AC}^{ti} - the foreseen value of the switching device that substitutes the used device supposed to intense maneuvers in year of change t_i [MU];
W_{AC}^{ti} - remanent value of the usage device unaffected in t_i year, [MU].

5. Application

The single – wire scheme of the transformer station is presented in fig. 3.
It is established the existence of two configuration, of “2 x 100%” (PT1 and PT2), and the second configuration of “n + 1” type PT3 + PT4 +PT9 = (3 + 1) and PT (5 ÷ 8) + PT 10 + PT11 = (5 + 1). The loading curves are presented in fig. 4. The input power P_i, and the utilization coefficients of the input power (K_u) on technological sectors are presented in table 1, as well as the characteristics of the transformers are in table 2. For the analyzed consumers, in function with the interruption moment, (T_{Cr0} = 8.33 x 10^{-4} h =3 s), the following critical moment is T_{Cr1} = 0.05 h [6, 7], that justifies the adoption of the value of T_{dm} = 0.05 h. In exploitation were determinate the indices of λ_j and μ_j [3].

The analyzed consumer is for construction of machine tools and has receivers of electric energy for basic processes: founding, forging, mechanic cold work, thermal treatment and galvanization, as well as receivers for insure the general conditions of the technological processes from the machine building. In [3], are given the specific indices for characteristically processes of the analyzed consumer.

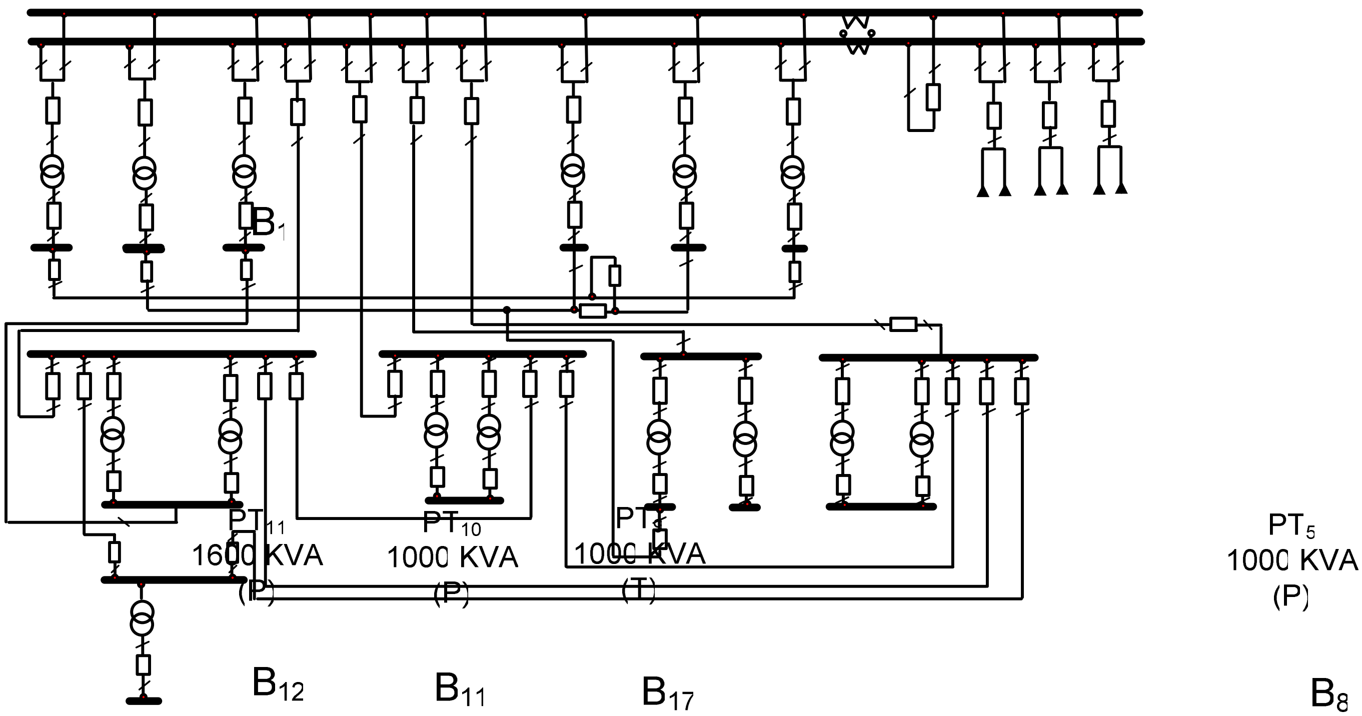


Fig. 3 – Single wire scheme of 6 / 0.4 kV transformer for supplying with electric energy of the analyzed enterprises: T – founding, F – forging; P – chip removing process; TR – treatment; G – galvanization; C – computer

Other calculating elements:

λ = 0.03 kW/kVA; $\overline{K}_{Et}$ = 0.13 €/kWh; τ = 7200 h; $N_R + N'_R = 300$;

$C_t + C'_t = 0.066\,(\overline{V}_{Ii} + \overline{V}'_{Ii}) = 2.43$ thousand €.

$\overline{V}_{Ii}, \overline{V}'_{Ii}$ average value of the switchers of MV and LV ($\overline{V}_{Ii}$ = 29.17 thousand €, $\overline{V}'_{Ii}$ = 7.67 thousand €). If aren't given the necessary data by the application of (14) aren't taking into account the terms of ΔI_{12t}, ΔI_t and W_{rt}.

The results of the computing for configuration of "2 x 100%" are presented in table 3.

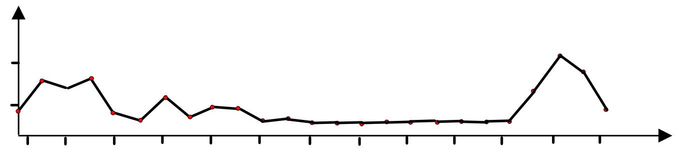
By evaluating of the damage, (ΔD_{12t}), it was considered the component D_4 too [3]. The calculation was made for three values of T_{CR} parameter: $8.33\ 10^{-4}$ h (corresponding to ASR system), 0.1 h (when the commutation of the reserve supplying is made manually, for the switchers) and 2.5 h (after when will be put in operation the failed path). To dispose of comparative elements, for the transformers which disservice all technological sectors, it was analyzed the configuration of 2 x 630 kVA too (TR + G), that doesn't exist in the actual situation, but it is possible. In optimal states the operation of the transformer station, leads to obtaining of some saving about 1950 MWh / year viewing the states all of the operating transformers.

Table 1 – Consume characteristics on technological sectors

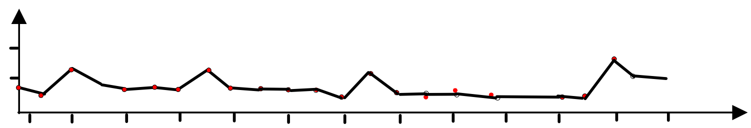
Technologic sector / Indices	T	F	P		TR	G
			Total	**PT_1**		
P_i [kW]	1751	265	7422	1866	1988	198
K_u	0.18	0.22	0.14	0.1	0.15	0.15

Table 2 – Characteristics of the transformers

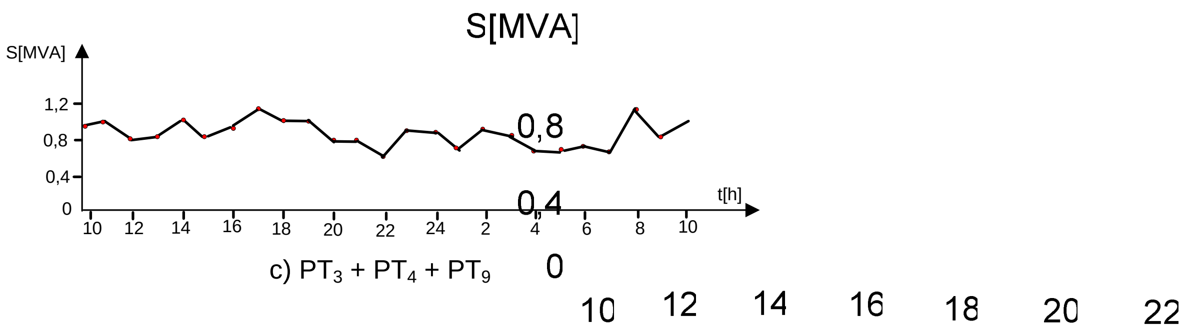
S_n[kWA]	U_{1n} / U_{2n} [kV/kV]	ΔP_F [W]	ΔP_W [W]	ΔU_{SC} [%]	I_0 [%]
630	6/0.4	1700	9900	6	4.8
1000	6/0.4	2730	14100	6	4.1
1600	6/0.4	3900	21000	6	3.5



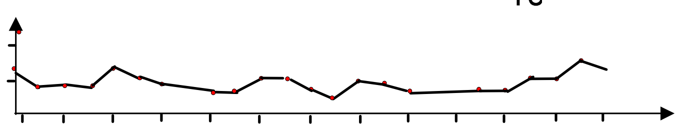
a) PT_1



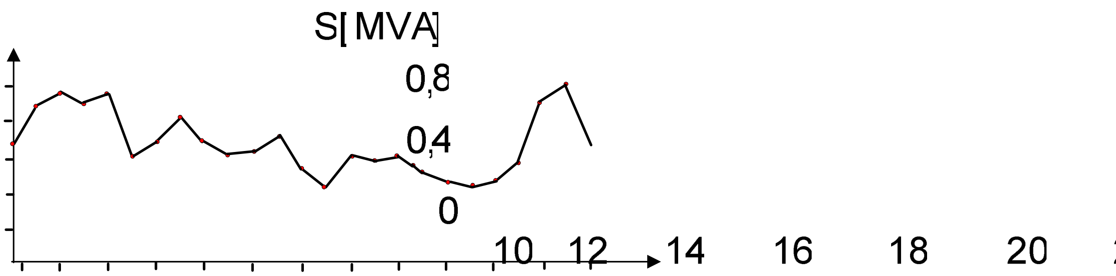
b) PT_2



c) $PT_3 + PT_4 + PT_9$



d) PT_5



e) $PT_5 + PT_6 + PT_7 + PT_8 + PT_{10} + PT_{11}$

Fig. 4 – Loading curves on transformers and transformer groups

Table 3 – Element of calculus for configuration “2 x 100%”

Calculus elements / Existent configuration	$\frac{S_e}{S_{e\lambda}}\left[\frac{kVA}{kVA}\right]$	ΔD_{12t} [thousand €] at T_{CR} [h]			$\frac{\Delta N_{12t}}{\Delta C12t}$ [1/thous and €]	$\frac{S_{e\lambda D}}{S^{C}_{e\lambda D}}\left[\frac{kVA}{kVA}\right]$ at T_{CR} [h]			Operation state	
		$8.33\ 10^{-4}$	0.1	2.5		$8.33\ 10^{-4}$	0.1	2.5	basic	occasional
2x1000 kVA (P)	$\frac{622}{706}$	6.87	6.95	7.85	$\frac{78.25}{2.55}$	$\frac{705}{705}$	$\frac{705}{705}$	$\frac{705}{705}$	1	2
2 x 630 kVA (F)	$\frac{369}{433}$	0	0.016	0.16	$\frac{234.75}{7.65}$	$\frac{433}{432}$	$\frac{433}{432}$	$\frac{433}{432}$	1	2
2 x 1000 kVA (T)	$\frac{622}{706}$	0	0.019	9	$\frac{156.5}{5.1}$	$\frac{706}{705}$	$\frac{706}{705}$	$\frac{705}{704}$	2	1
2 x 630 kVA (TR + G)	$\frac{369}{433}$	0	22.85	69.77	$\frac{234.75}{7.65}$	$\frac{433}{432}$	$\frac{431}{430}$	$\frac{428}{426}$	1	2

Conclusions

The stations of MV / LV used to supply the industrial consumers with electric energy, includes the following typical configurations: “2 x 100%” and “n + 1” - by applying the criterion of “total updated costs”.

Referring on the configuration “2 x 100%”, it was deduced two relations for calculation of input power at which is justified the switching from the passive reserve state to active reserve state and inverse. In relation (12) are the following factors: proper technological consume and safety level, and relation (14) includes the supplementary costs too. The appreciation of the values for the mentioned factors is detailed, in this paper, by relations and indices of the analyzed domain. A result is that in conditions of some normal supplementary maneuvers (1 ÷ 5 /day), the values of the powers at which are justified the switching between the two states, results through application of criteria TUC, have relative small displacement (1 ÷ 10 kVA) referring to the stabilized values by application of criterion “minimal power losses”. The mentioned deflection, are in function with time after when is connected the reserve supplying and of specifics of the sectors. The made evaluations, presents that by introducing of all implied factors the reservation mode in “2 x 100%” configuration is stabilized basing on the load curve, so isn’t justified the active reserve state the permanently operation.

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