INDIVIDUAL COMPENSATION FOR REACTIVE POWER LOSSES OF 10/0.4 KV DISTRIBUTIVE TRANSFORMERS

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SUMMARY

The effects of installed non-regulated capacitor banks at low voltage in TS 10/0.4 kV on the consumption area of "Power Supply Company" Leskovac are analyzed in this paper. Installing capacitor banks had commenced before the "Serbia Power Distribution System Integral Operative Program" (IOP) for reduction of non-technical losses and was continued and finished in 2005.

The benefits from taken reactive power in 2005, compared to 2004, and the global approach to reducing losses are presented. Regarding reduction of active power losses, the necessary compensation degree is reached, while at the same time the effects on the network are taken into consideration. The optimal compensation power for losses of distributive transformers 10/0.4 kV reactive power is proposed.

The technical and economic equivalent of reactive power is defined.

Keywords: Compensation for reactive power losses, compensation degree, technical equivalent of reactive power, economic equivalent of reactive power, power losses.

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INTRODUCTION

One of the ways to reduce the active power losses is to affect the reactive power flows. Installing capacitor banks in distributive TS 10/0.4 kV enables conducting reactive power compensation, which also contributes to reducing active power losses to some extent.

The procedure of installing non-regulated capacitor banks at low voltage in TS 10/0.4 kV had commenced before the “Serbia Power Distribution System Integral Operative Program” (IOP) for the reduction of non-technical losses. From the total amount of procured reactive power from transmission network, a significant part was spent by distributive transformers 10/0.4 kV. 20.25% from the total amount of procured reactive power in 2005 was spent on magnetizing the nuclei of these transformers. Therefore, the aim of the compensation was to completely compensate for the reactive energy and enable that it depends solely on transformer load and to cover the losses in coils.

The installed capacitor banks are non-regulated. They are also permanently connected to low voltage convergence devices in TS 10/0.4 kV.

This paper stemmed from the achieved effects and it provides a theoretical basis to the reactive power compensation process. It defines a complete methodology of determining compensation degree, as well as the change in active power losses which occurs after the compensation.

REDUCING THE COSTS OF TAKEN REACTIVE POWER

Individual reactive power compensation is a necessary activity to be conducted in order to reduce the active power losses within the network, the secondary effect of which would be the improvement of power factor.

Having injected ten additional MVAr in 2005, the average power factor of taken electric power on the “Power Supply Company” Leskovac consumption area amounted to 0.925, whereas it was 0.898 in 2004. In the process, 41,153,664 kVArh less reactive energy was purchased, which represents 13.83%. Since the price of reactive energy on taking over increased (0.2 din./kVArh), the purchase costs were reduced for 8,230,732.80 dinars.

METHODOLOGY FOR DETERMINING THE COMPENSATION DEGREE

The equivalent transformer scheme is shown in figure 1.

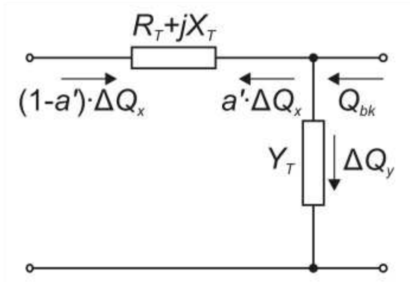

Figure 1. Equivalent transformer scheme

The losses of transformer reactive power consist of two components:

- the component of losses on transformer magnetizing ΔQ_y;
- the component of losses on scattering in transformer coils ΔQ_x.

Therefore, the total amount of transformer reactive power losses represents the sum of individual components:

$$\Delta Q = \Delta Q_y + \Delta Q_x \,. \tag{1}$$

The flow ΔQ_y component depends on the specified transformer power S_n and the percentage value of current of transformer idle speed i_0 [%]:

$$\Delta Q_y = \frac{i_0[\%]}{100} \cdot S_n \,. \tag{2}$$

This value is completely independent of transformer relative load and can be completely compensated for with the same value of capacitor bank reactive power. The choice of equivalent scheme is based on this assumption.

The progression component ΔQ_x can be represented through the following relation:

$$\Delta Q_x = \frac{u_k[\%]}{100} \cdot S_n \cdot \left(\frac{S}{S_n}\right)^2 = \Delta Q_{x,n} \cdot \beta^2 \,, \tag{3}$$

where:
u_k [%] – percentage value of the transformer short circuit voltage;
$\beta = \frac{S}{S_n}$ – the quotient of transformer relative load.

It is obvious that the progression component depends on the current load of the transformer; therefore, it is necessary to determine the degree to which compensation should be conducted. In order to simplify the calculation, the voltage of low voltage side of the transformer will be considered constant. The power factor of connected receivers will also be considered constant in order not to disturb the relation between transformer reactive power expenditure and connected capacitor bank with reactive powers flow.

The connected capacitor bank should completely cover the reactive power losses on transformer magnetizing ΔQ_y, as well as the changeable part of losses on coils $a'\Delta Q_y$, where we have $0 \le a' \le 1$.

$$Q_{bk} = \Delta Q_y + a' \cdot \Delta Q_x \,. \tag{4}$$

The compensation degree *a* is determined in the following way:

$$a = \frac{Q_{bk}}{\Delta Q} = 1 - (1 - a')\frac{1}{\dfrac{\Delta Q_y}{\Delta Q_x} + 1}. \tag{5}$$

Reactive power compensation will reduce the reactive component of transformer current, which will reduce the total transformer current and, accordingly, active power losses. Prior to compensation, the active power losses within the transformer caused by reactive power losses flow within the same transformer amount to:

$$\Delta P'_T = R_T \frac{\Delta Q^2}{U^2} = \frac{R_T}{U^2}(\Delta Q_x + \Delta Q_y)^2. \tag{6}$$

The network before the transformer can be represented by resistance R_M, the value of which can be calculated based on the data on the length *l* [km] and length line resistance *r* [Ω/km]:

$$R_M = r \cdot l. \tag{7}$$

Taking into consideration the active power losses within the network caused by reactive power flow ΔQ_y, the relation (6) can be corrected and then the losses are:

$$\Delta P' = \frac{R_T + R_M}{U^2}(\Delta Q_x + \Delta Q_y)^2. \tag{8}$$

After the compensation, the active power losses component is:

$$\Delta P'' = \frac{R_T + R_M}{U^2}\left[\Delta Q_x + \Delta Q_y - a(\Delta Q_x + \Delta Q_y)\right]^2 = \frac{R_T + R_M}{U^2}(1-a)^2(\Delta Q_x + \Delta Q_y)^2. \tag{9}$$

Observing the costs of losses enables to determine the degree to which compensation is economically justifiable. Without compensation, the costs of losses are:

$$c'_0 = K_m \cdot c_{p,Cu} + \tau' \cdot c_e, \tag{10}$$

Where:

$K_m = r^2$ – the relation of active power losses at the moment of maximum power of the measuring site for the observed distribution system and the greatest power losses at the $R_T + R_M$ resistance;

$c_{p,Cu}$ [din./kW] – the price of power losses in copper, expressed through maximum simultaneous power of the measuring site, i.e. distribution system;

τ' [h] – equivalent time of maximum losses duration;

c_e [din./kWh] – electric power price.

Introducing compensation changes the price of losses, for now $K'_m = \dfrac{(r-a)^2}{(1-a)^2}$, whereas time of maximum losses duration is τ. It now equals:

$$c''_0 = K'_m \cdot c_{p,Cu} + \tau \cdot c_e. \tag{11}$$

The necessary power of the capacitor bank is:

$$Q_{bk} = \Delta Q_y + a' \cdot \Delta Q_x = a \cdot (\Delta Q_y + \Delta Q_x), \tag{12}$$

Whereas yearly expenses would be:

$$T''(a) = Q_{bk} \cdot t_{bk}. \tag{13}$$

The value t_{bk} represents capacitor bank expenses and is calculated from the following relation:

$$t_{bk} = (p_n + p_o + p_a)(K'_{bk} + K'_M) + c_{bk}\,, \tag{14}$$

Where:
p_n – normative efficiency rate;
p_o – yearly maintenance rate;
p_a – yearly depreciation rate;
K'_{bk} [din./kVAr] – specific price of a capacitor bank;
K'_M [din./kVAr] – specific price of bank installation and transport;
c_{bk} [din./kVAr] $= \Delta p_{bk}(c_{p,Cu} + T_g \cdot c_e)$ – specific price of losses within the capacitor bank;
Δp_{bk} [kW/kVAr] – specific active power losses within the bank;
T_g [h] – yearly usage time which is 8760 h for constantly operating banks.

In order to determine the optimal compensation degree, the function of costs difference before and after the compensation needs to be determined in a function of compensation degree, $\Delta T(a)$:

$$\Delta T(a) = \frac{R_T + R_M}{U^2}(\Delta Q_x + \Delta Q_y)^2 \left\{ (r^2 c_{p,Cu} + \tau' c_e) - (1-a)^2 \left[\frac{(r-a)^2}{(1-a)^2} c_{p,Cu} + \tau c_e \right] \right\} - a(\Delta Q_x + \Delta Q_y)\, t_{bk} \tag{15}$$

Maximum costs difference function value can be determined by equalizing the first function derivative to the power of compensation with zero $d(\Delta T(a))/d\,a = 0$:

$$a = \frac{r\, c_{p,Cu} + \tau c_e}{c_{p,Cu} + \tau c_e} - \frac{t_{bk}\, U^2}{2(R_T + R_M)(\Delta Q_x + \Delta Q_y)} \cdot \frac{1}{c_{p,Cu} + \tau c_e}\,. \tag{16}$$

Based on the electric power and capacitor banks prices, the value of the second term is indefinitely smaller than the first one; therefore it can be neglected for simplified analyses. The error made this way is very small (below 0.5%), so the value of compensation degree amounts to:

$$a = \frac{r\, c_{p,Cu} + \tau c_e}{c_{p,Cu} + \tau c_e}\,. \tag{17}$$

The optimal compensation power now amounts to:

$$Q_{bk} = \frac{r\, c_{p,Cu} + \tau c_e}{c_{p,Cu} + \tau c_e} \cdot (i_0\,[\%] + \beta^2 u_k\,[\%]) \cdot \frac{S_n}{100}\,. \tag{18}$$

When adopting the necessary value for Q_{bk}, it is necessary to take into consideration the standard scale of denominator values of capacitor banks.

The question is for which value of β transformer load Q_{bk} should be determined, for considered capacitor banks are non-regulated. The best solution is to determine the compensation of each transformer individually, according to its chronological load diagram, and maximum load duration diagram.

REACTIVE POWER TECHNICAL AND ECONOMIC EQUIVALENT

The reactive power flow from the source (this is considered to be the measuring site towards power distributor) to the distributive transformer, in order to cover reactive power losses within the transformer, causes additional active power losses in the network.

The active power losses component which depends on the reactive power flow is shown in the relation (8) before the compensation and with the relation (9) after the compensation. In order to simplify the formula, it has been considered so far that the power factor of transformer load is cosφ = 1, i.e.

reactive transformer load Q_T has not been taken into consideration. Considering Q_T, the change of active power losses is:

$$\Delta P = \frac{R_T + R_M}{U^2} \cdot Q_{bk} \cdot \left[2(\Delta Q_x + \Delta Q_y + Q_T) - Q_{bk}\right], \tag{19}$$

whereas the reactive power which reduces them equals the capacitor bank power Q_{bk}.

The term of reactive power economic equivalent is mentioned in references [2], [5] and it is defined as:

$$\sigma\ [\text{kW/kVAr}] = \frac{\partial(\Delta P)}{\partial Q_{bk}}. \tag{20}$$

Introducing technical equivalent of reactive power is suggested and it is defined as:

$$\gamma\ [\text{kW/kVAr}] = \frac{\Delta P}{Q_{bk}}, \tag{21}$$

that does not consider economic aspects of compensation. Even though σ and γ are the same in terms of their dimensions, in further text it is obvious that it should be differentiated between them.

Applying relations (21) and (20) to relation (19), σ and γ for distributive transformer 10/0.4 kV:

$$\sigma = 2 \cdot \frac{R_T + R_M}{U^2} \cdot (\Delta Q_x + \Delta Q_y + Q_T - Q_{bk}) \tag{22}$$

and

$$\gamma = \frac{R_T + R_M}{U^2} \cdot \left[2\,(\Delta Q_x + \Delta Q_y + Q_T) - Q_{bk}\right]. \tag{23}$$

The dependence relation between ΔP and Q_{bk} is presented.

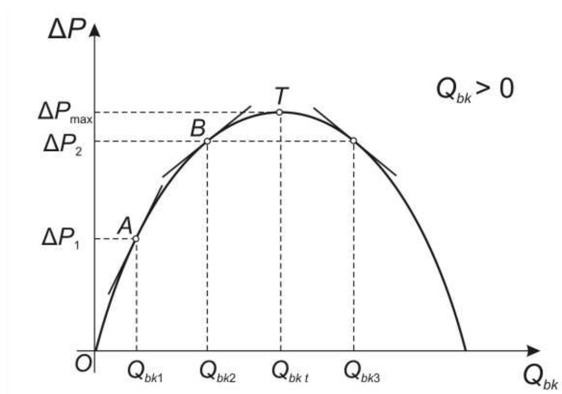

Figure 2. Active power losses dependence in a function of capacitor bank reactive power

It is obvious from figure 2 that the greatest reduction of power losses $\Delta P_{\max}$ is for the value $Q_{bk\,t}$. For the T point it is:

$$\gamma_T = \frac{\Delta P_{\max}}{Q_{bk\,t}}, \tag{24}$$

and for the B point it is:

$$\gamma_B = \frac{\Delta P_2}{Q_{bk\,2}}. \tag{25}$$

It is obvious that, following the rising part of the curve in picture 2, the γ value decreases, for, the closer we approach to the T point, relatively small ΔP increases are obtained for relatively big Q_{bk} increases. Even though the ΔP increases, which leads to $\Delta P_{\max}$ value, it is accomplished with relatively big Q_{bk} increase.

Therefore, it is justifiable to introduce reactive power economic equivalent defined in relation (20). The σ value in the T point equals zero, which indirectly points to the fact that compensation should not be conducted to the T point, because this is where economic equivalent is the lowest. It is obvious from the picture that the ΔP_2 is achieved with the Q_{bk3} which gives the negative value to the σ; therefore, the over-compensation is achieved, which is not worthwhile.

NUMERICAL EXAMPLE AND RESULTS ANALYSIS

In order to illustrate the effect of reactive power compensation on reduction of active power losses, the reactive power compensation of an individual distributive transformer will be considered, as well as the effect it has on the power line with equal load.

Distributive transformer 10/0.4 kV

According to [6], for standard data of power transformers, the capacitor banks values for compensation of their reactive power consumption are recommended. The overview of these values is shown in table 1.

TABLE 1 - Standard distributive transformers 10/0.4 kV data

S_n [kVA]	i_0 [%]	u_k [%]	P_k [kW]	Q_{bk} [kVAr]
250	1.8	4	3.25	20
400	1.6	4	4.6	30
630	1.3	4	6.5	40

Taking into consideration the fact that injecting capacitor banks in TS 10/0.4 kV within the IOP was conducted using the values according to Technical Recommendation [6], so that it was not insisted upon economic equivalent of reactive power, only technical equivalents of reactive power for β = 1 and cosφ = 1 and 0.95 will be shown.

TABLE 2 – Technical equivalent of distributive transformers reactive power

$\gamma \cdot 10^{-3}$ [kW/kVAr]	β = 1	
	cosφ	
S_n [kVA]	1	0.95
250	0.468	8.586
400	0.425	7.607
630	0.438	6.882

The power line with equal load

This simple hypothetical example could be applied on most 10 kV feeders in the “EPS” distribution networks. It is considered that the line with cross section s [mm^2] is equally loaded with the n transformer with power S_n [kVA], on the average distance l [km]. The power factor of all transformers is equal and constant. Reactive power compensation can be conducted on every transformer. Furthermore, the effect of reactive power compensation can be seen on the whole feeder, represented by technical equivalent of reactive power. The example is shown in picture 3.

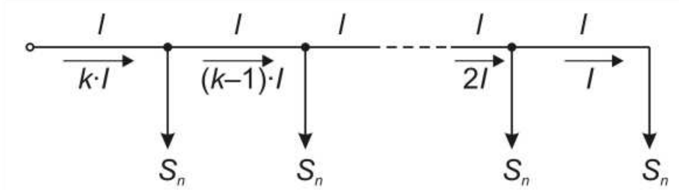

Figure 3. Power line with equal load

If the current at the end of the line equals *I,* then, due to equal load, the current through each section of the line equals $k\cdot I$ ($1\le k\le n$); therefore the reactive load component by each section equals $k\cdot(\Delta Q_x+\Delta Q_y+Q_T)$. The relations for active power losses before and after compensation, in accordance with the relations (8) and (9), have to be applied separately to the power line and transformers. Reduced active power losses in the line are expressed by relation that has one more term which includes reactive loads of each line section:

$$\Delta P_v = \frac{R_M}{U^2}\cdot Q_{bk}\cdot\left[2(\Delta Q_x+\Delta Q_y+Q_T)-Q_{bk}\right]\cdot\sum_{k=1}^{n}k^2,\quad (1\le k\le n;\ k,n\in N)\,, \tag{26}$$

or

$$\Delta P_v = \frac{R_M}{U^2}\cdot Q_{bk}\cdot\left[2(\Delta Q_x+\Delta Q_y+Q_T)-Q_{bk}\right]\cdot\frac{n(n+1)(2n+1)}{6},\quad (n\in N)\,, \tag{27}$$

whereas:

$$\sum_{k=1}^{n}k^2 = \frac{n(n+1)(2n+1)}{6},\quad (1\le k\le n;\ k,n\in N)\,. \tag{28}$$

Reduced transformers active power losses are:

$$\Delta P_T = \frac{R_T}{U^2}\cdot Q_{bk}\cdot\left[2(\Delta Q_x+\Delta Q_y+Q_T)-Q_{bk}\right]\cdot n,\quad (n\in N)\,. \tag{29}$$

Now, the reactive power which reduces total active power losses ($\Delta P=\Delta P_v+\Delta P_T$) is $n\cdot Q_{bk}$. Therefore, according to the relation (21), technical equivalent of reactive power is:

$$\gamma = \frac{2(\Delta Q_x+\Delta Q_y+Q_T)-Q_{bk}}{U^2}\cdot\left[R_M\,\frac{(n+1)(2n+1)}{6}+R_T\right],\quad (n\in N)\,. \tag{30}$$

In order to calculate the above example, the numerical values in table 3 will be used, also taking into consideration transformer data in table 1.

TABLE 3 – Data on power line with equal load, [6]

S_n [kVA]	s [mm^2]	l [km]	r [Ω/km]	n
250	35	2	0.91	8

Using relations (2), (3), (7) and (30), for different values of β and cosφ, the values for technical equivalent of reactive power can be determined. The obtained results provide benefit on the entire 10 kV feeder and are given in table 4.

TABLE 4 – Reactive power technical equivalent for power line with equal load

$\gamma\cdot10^{-3}$ [kW/kVAr]	β = 1	
	cosφ	
S_n [kVA]	1	0,95
250	4.6449	85.2210

CONCLUSION

In order for the compensation to be optimal, good knowledge of load diagram for both active and reactive power is necessary, which would enable choosing an adequate capacitor bank.

Determining reactive power technical equivalent for a particular network enables reduction of active power losses by a reactive power unit of a capacitor bank. Reactive power economic equivalent determines the degree of compensation. It represents the connection between reactive power technical equivalent and the necessary degree of compensation which includes economic indexes of compensation.

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