Settlement of reactive power compensation in the light of white certificates

Konrad Zajkowski[1,*]

[1]Koszalin University of Technology, DP of Energy, 15-17 Raclawicka St. 75-620 Koszalin, Poland

Abstract. The article discusses the problem of the determination of savings on active energy as a result of a reactive power compensation. Statutory guidance on the required energy audit to obtain white certificates in the European Union was followed. The analysis was made on the basis of the Polish Law. The paper presents a detailed analytical method and an estimation method taking into account the impact on the line, the transformer and the generator. According to the relevant guidelines in the European Union, the reduction of CO_2 emissions by calculating the saving of active power should be determined.

The detailed method and an estimation method proposed for the determination of savings on active energy as a result of the reactive power compensation carried out possess some errors and inconvenience. The detailed method requires knowledge of the network topology and a determination of reactive power Q at each point of the network. The estimation method of analysis is easy in execution, especially if the consumer of energy is the main or the most significant purchaser of electricity in the network. Unfortunately, this latter method can be used only for activities that do not require high computational accuracy. The results obtained by this method are approximate values that can be used for the calculation of economic indicators. The estimation method is suitable for determining the number of white certificates when a power audit concerns a recipient of electricity, the structure of which is a large number of divisions scattered at many different locations in the power system.

1 Introduction

In Europe, the white certificates are a market tool for improving energy efficiency. This is document demonstrating energy savings as a result of investments to improve energy efficiency.

The investments that reduce the production of electricity, which reduces the negative impact on the environment is one of activities. An energy audit is an element that makes the settlement of the actions undertaken possible. The relevant guidelines are set out in the following regulations: [1-6].

Among the many energy efficiency improvement measures [7] that make it possible to apply for white certificates, is to limit the flow of reactive power [2]. This action consists in performing size electrical measurements and analysing the location of the compensation devices.

The subject of energy savings is active energy, which is saved by the action of reducing the flow of reactive energy. The effect of reducing the reactive power is to reduce the active power in the form of energy losses on the power grid.

An engineering approach in this area will involve a determination of savings on primary energy (individually on each grid element) being the result of reducing reactive power flows.

2 Methodology

An analysis in a detailed and simplified audit should be prepared by means of the balance method [2]. It is important to analyze the components in the energy distribution system by selecting the shortest route connecting the generator to the power compensation location.

Two calculation methods will be presented: detailed (sections 2.1 - 2.4) and estimation (sections 2.5 - 2.6). In section 3, a computational example using the estimation method proposed by the author is presented.

2.1 Transmission line section

Reactive power flows through a line segment cause:
  - a limitation of the active power transfer,
  - an increase of active power losses,
  - an increase of current and voltage drops,
  - difficulties in the work of grid elements.

The transmission line can be described with impedance $R + jX$. This approach was presented by the authors in the following positions: [8-13].

The active power P is absorbed by the receiver (Fig. 1), and for the reactive power Q, the receiver is a prosumer (receiver or supplier). Both the active and reactive power generated by the receiver affect

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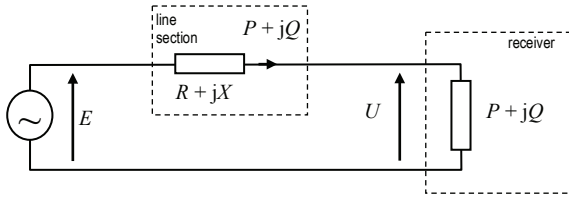   Corresponding author: konrad.zajkowski@tu.koszalin.pl

Fig. 1. Mathematical model of the section of the power line.

the ΔP power losses on the $R + jX$ impedance:

$$\Delta P = \frac{P^2 + Q^2}{U^2} R. \qquad (1)$$

When the compensator is added (Fig. 2), the reactive power passing through the line is reduced.
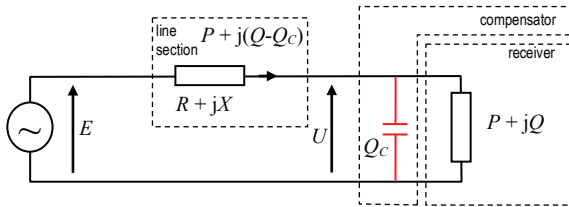
$$Q' = Q - Q_C. \qquad (2)$$

Fig. 2. Mathematical model after compensation.

Typically, this power is not reduced to zero. With partial compensation, the remaining reactive power continues to load the flow. The difference between the active power loss (1) determined prior ΔP and after $\Delta P'$ compensation is a profit on δP_P active power:

$$\delta P_P = \Delta P - \Delta P' = \frac{2QQ_C - Q_C^2}{U^2} R, \quad \delta A_P = \delta P_P \cdot T_p, \qquad (3)$$

where: Q_C – power of compensator, δA_P – active energy, T_p – work time of compensator Q_C.

In the mth section of the transmission line, the loss of active power is dependent on the power transmitted by the next line section (Fig. 3):

$$\delta P_{P(m)} = \frac{Q_{(m+1)}^2 - Q_{(m+1)}'^2}{U_{(m)}^2} R_{(m)}, \qquad (4)$$

where: $Q_{(m+1)}$ – reactive power transmitted from $m+1$ system, $Q'_{(m+1)}$ – reactive power from $m+1$ system after switching on the compensator in the receiver.

The reactance in the $m+1$ section changes the reactive power acting on the mth section. Analogically, the reactive power is changed after the compensation Q'.
Due to the variability of the parameters over time, the values given in formulas (3) and (4) are values averaged over the T_p time interval. To determine the economic profit resulting from the compensation should be known:

- network topology,
- the length of the mth section of the line,
- the conductor cross-section area,
- the conductivity of the conductive material,
- reactive power before $Q_{(m)}$ and after $Q'_{(m)}$ the compensation.

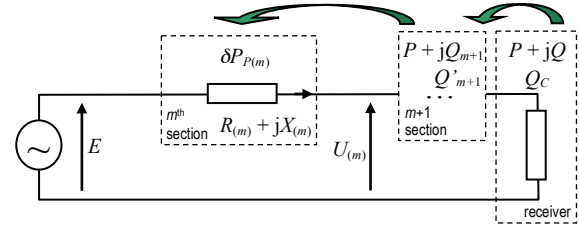Unfortunately, for all network elements this data is often not available.

Fig. 3. Impact between network segments.

2.2 The transformer

The transformer for the power line is the R_T resistance at which the loss of active power takes place. This loss is described in formula (1). Reactive power flows through the transformer cause an increase of active power losses in the transformer. Load losses ΔP_{oT} in a three-phase transformer are the result of the flow of current I through the winding:

$$\Delta P_{oT} = 3I^2 R_T. \qquad (5)$$

When the current is equal to the I_{nT} nominal current, the load losses will be:

$$\Delta P_{onT} = 3I_{nT}^2 R_T. \qquad (6)$$

From equations (5) and (6), a relationship is obtained which allows the loss to be measured at any transformer load:

$$\Delta P_{oT} = \Delta P_{onT} \left(\frac{I}{I_{nT}}\right)^2 = \Delta P_{onT} \left(\frac{S}{S_{nT}}\right)^2, \qquad (7)$$

where from the transformer's datasheet: ΔP_{onT} – nominal load power dissipation, S_{nT} – nominal power of the transformer.

The savings on the active power losses in the mth transformer using the reactive power compensation in the receiver equals the loss difference before and after the compensation:

$$\delta P_{T(m)} = \Delta P_{onT(m)} \left(\frac{Q_{(m+1)}^2 - Q_{(m+1)}'^2}{S_{nT(m)}^2}\right). \qquad (8)$$

Thus, the gain on active energy in the mth transformer is:

$$\delta A_{T(m)} = \delta P_{T(m)} \cdot T_p. \qquad (9)$$

The parameters $Q_{(m+1)}$ and $Q'_{(m+1)}$ in formula (8) is to be understood as reactive power at the output of the

preceding segment, which may be another transformer or preceding a power line segment (same as shown in Fig. 3).

In chapters 2.1 and 2.2, the change in active power caused by the impact of individual sections of the power system (transformer or line segment) has been omitted. These chapters also omit the change in the voltage value $U_{(m)}$ that occurs when the compensator is connected.

2.3 The generator

The effect of reactive power from the segment preceding the generator, causes a reduction the ability to produce active power. When the power factor is less than nominal, it is impossible to use the full power of the turbine due to the thermal load of the generator. An increased reactive power flow causes a demagnetization of the rotor and a reduction of the electromotive force of the generator.

In the case of asynchronous generators, reactive power must be supplied from the network or from the compensator with an individual compensation.

In practice it is difficult to estimate the demand for reactive power of each segment in the power system. Due to the existence of the reactance of individual section in the system, reactive power is required and can't be completely zero.

To determine the influence of power in the generator is the use of similarities in electrical properties between the transformer and the generator.

$$\delta A_G = \delta P_G \cdot T_p = \Delta P_{onG}\left(\frac{Q_{(m+1)}^2 - Q_{(m+1)}^{'2}}{S_{nG}^2}\right)T_p. \quad (10)$$

where: ΔP_{onG} – load losses at a nominal current flow through the generator, S_{nG} – nominal power of the generator.

The production costs of reactive power in generators are substantially smaller than in receivers. However, the production of reactive power in the generator increases

the transmission costs of reactive power in the network. Therefore, from an economic point of view, the production of reactive power in the generator and its transmission to customers is unprofitable.

2.4 Energy savings in all system segments

Energy saving δA that results from the reduction of active power losses in all the parts of the network by using the reactive power compensation of the receiver requires knowledge of the network topology and the determination of (4), (8) and (10):

$$\delta A = \delta A_G + \sum_m \left(\delta A_{P(m)} + \delta A_{T(m)}\right). \quad (11)$$

Determination of value (11) requires:
- knowledge of network topology,
- measurement of $Q_{(m)}$ power at each point of the network,
- knowledge of the change in reactive power $Q'_{(m)}$ caused by the Q_C power compensation in the receiver.

This information is not available for every point in the network. In practice, the reactive power $Q'_{(m)}$ can't be measured. The powers $Q_{(m)}$ and $Q'_{(m)}$ can be determined analytically, but this requires detailed information about the entire network.

2.5 The energy equivalent of reactive power

Inclusion in the calculations of additional current flows, ie: a complete power grid structure with several generators and multiple receivers, results in additional computational complexity calculations.

A solution to this problem might be the use of the ratio (Fig.4) which was determined in the mid twentieth century: *the energy equivalent of reactive power* [14-16]. This ratio is defined as the differential of the active power losses in relation to reactive power.
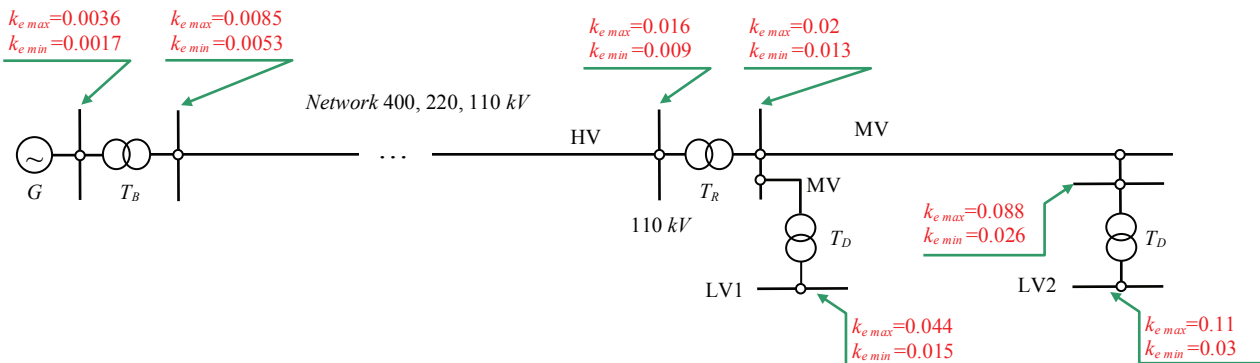

Fig. 4. The values of the energy equivalent of reactive power estimated in 2007 [7].

$$k_e = \frac{\delta}{\delta Q}\Delta P = \frac{2Q}{U^2}R \quad \left[\frac{kW}{kVAr}\right]. \tag{12}$$

The value of coefficient k_e strongly depends on reactive power, and it varies with changes to this power. This quantity permits one to calculate the change of active power losses caused by changes to reactive power that is collected at a given point in the network. The value of this factor depends from the value of reactive power and the distance of the point analyzed to source, whose measure is resistance R. According to the literature [9] and [12], the value of this coefficient is determined for the minimum and maximum reactive power loads (Fig.4).

Due to the variability of the load, the average value of the reactive power energy equivalent in a given network node is accepted in calculations:

$$k_{e\,avg} = \frac{k_{e\min} + k_{e\max}}{2}. \tag{13}$$

In order to estimate how much power losses are reduced in the grid that supplies a given network point as a result of the installation of a battery of condensers, it is enough to multiply the value of the reactive power energy equivalent for this point by the power of the battery installed.

The reduction amount of losses is calculated from the following formula:

$$\delta P = k_{e\,avg}\cdot Q_C, \quad \delta A = \delta P\cdot T_p. \tag{14}$$

The equivalent of reactive power k_e is an economic tool. It is an indicator approximating many of the phenomena discussed in sections 2.1 – 2.4 (only the most important has been discussed). Using this factor, the calculations are error-prone, the value of which depends on the accuracy of the determination of k_e.

The value of the energy equivalent of reactive power k_e depends from the following:

- the distance of the point analyzed in the network (the resistance path from the generator to the point analyzed in the network),
- the load of the network - an adoption of the arithmetic average of the minimum and maximum values is only a partial correction of an error in estimation,
- network topology and its complexity.

This means that an estimation of the reduction of losses based on the energy equivalent of reactive power is burdened with significant errors. The latest k_e values are the result of random testing for a limited part of the power system and were performed in 2007 [7].

Due to considerable computational uncertainty, this coefficient allows you to know only the range of power values. However, there are situations where the use of this indicator is necessary. For example, when you need to designate economic indicators that account for the installation of compensator that are connected to the network and:

- the exact structure of the network is unknown,
- it is not possible to count the currents and energy losses on individual network segments (see section 2.4),
- an economic task involving a very large number of recipients.

Approximate results are obtained when the k_e coefficient is used, so this calculation will be referred to as *estimation method*. Comprehensive calculations for each network member (see section 2.1 – 2.4) will be referred to as *detailed analytical method*.

2.6 Determination of primary energy savings

Determination of primary energy savings is needed to account for the economic effects of improving energy efficiency. It is possible to apply for white certificates, which are awarded by tender. They are documents that weigh actions to improve the energy efficiency of company's or state.

The saved active energy is prepared for one calendar year by making adequate measurements and calculations [2]. The values of the average energy determined in billing invoices can be used as input data. This can be determined when using advanced electronic energy meters, which possess separate individual records with a division into inductive and capacitive reactive power. For this purpose, it is best to accept the entire billing year in an analysis, including all the seasons, and which consists of i-billing periods.

When the estimation method is used, only inductive reactive power can be used, since the k_e coefficient is determined only for such power. Prior to compensation, the average power factor for inductive reactive power is:

$$\tan\varphi_{(i)} = \frac{A_{Q(i)}}{A_{P(i)}}, \tag{15}$$

where: A_Q - total inductive reactive energy read from the ith invoice, A_P - consumed active energy during this period.

The value of $\tan\varphi'$ after the compensation can be determined in two ways:

a) when there are invoices from the period after the compensation, this coefficient is calculated analogously to (15).

b) when there is no invoice after the compensation (settlement made before the compensator is enabled), the minimum value (e.g. 0.4) from contract, should be taken.

Assuming invariable active energy, after partial compensation there is still reactive energy, which is:

$$A'_{Q(i)} = \tan\varphi'\cdot A_{P(i)}. \tag{16}$$

Therefore, reactive power reduced by the compensator in the ith billing period is equal to:

$$A_{C(i)} = Q_C\cdot T_p = A_{Q(i)} - A'_{Q(i)}. \tag{17}$$

It is reactive inductive energy reduced by the battery of capacitors.

Taking the energy equivalent of reactive power determined for the point being the closest to compensation according to (14), the value of active power reduction in the network caused by compensation A_C in the ith billing period is as follows:

$$\delta A_{(i)} = k_{e\,avg} \cdot A_{C(i)}. \qquad (18)$$

Taking invoices for the whole year, the total final energy savings (within the meaning of the Act [1]) constitute the sum of active energy savings resulting from compensation:

$$\delta A = \sum_i \delta A_{(i)} \quad [kWh / year]. \qquad (19)$$

In accordance with the guidelines of the International Energy Agency (IEA) and the Organisation for Economic Co-operation and Development (OECD), the value of (19) expressed in the tons of oil equivalent (*toe*) is:

$$\delta A_{toe} = \frac{\delta A}{11630} \quad [toe / year]. \qquad (20)$$

The average annual primary energy savings referred to in [1] in accordance with [2] are equal to:

$$\delta A_p = \delta A \cdot w_i, \quad \delta A_{p\,toe} = \delta A_{toe} \cdot w_i, \qquad (21)$$

where: δA_p – the amount of primary energy savings expressed in primary fuel [*kWh / year*] or [*GJ / year*], δA – final energy savings, expressed in [*kWh / year*] or [*GJ / year*], w_i – effort ratio of non-renewable primary energy which depends from the final energy carrier (Tab.1).

The w_i factor is defined according to the fuel or energy source used in a given country, which according to [4] should be one of the values:

Table 1. Effort ratio of non-renewable primary energy for the production and supply of electric energy.

Way of producing electricity	w_i
mixed-mode production	3.0
production of electricity from solar energy	0.7

For a specified value of δA_p expressed in [*kWh / year*], the reduction of CO_2 emissions in a year is determined according to [5]:

$$\Delta E_{CO2} = \delta A_p \cdot 3.6 \cdot 10^{-3} \cdot we_{CO_2} \quad [kg / year], \qquad (22)$$

where: we_{CO2} – CO_2 emission factor for fuels.

The quantity of the reduction of CO_2 emissions is calculated using CO_2 emission factors contained in [5] and under the EU Emissions Trading System (EU ETS) for a given year (Table 2).

Table 2. Example we_{CO2} reference CO_2 emission factors for fuels [6] in accordance with the guidelines of the Intergovernmental Panel on Climate Change (IPCC) from the year 2006.

Fuel type	we_{CO2} $MgCO_2/TJ$	Fuel type	we_{CO2} $MgCO_2/TJ$
petroleum	73.3	coking coal	94.5
shale oil	73.3	lignite	101.1
gas / diesel oil	74.0	bituminous coal	94.2
ethane	61.6	natural gas	56.1
solvent naphtha	73.3	industrial waste	142.9
petroleum coke	97.5	waste oils	73.3
refinery gas	51.3	peat	105.9

A project aimed at an improvement of energy efficiency, as a result of which energy savings in (21) are obtained in an amount being an equivalent to at least 10 *toe* on average over the year, can be included in a tender [1]. Several projects of the same type aimed at an improvement of energy efficiency, as a consequence of which the total energy savings are achieved in the amount being an equivalent to at least 10 *toe* on average over a year, may be brought together.

3 Results

The proposed calculation method using k_e factor, which the author called the estimation method, was used to designate white certificates for one Polish company. This economic settlement covered some 350 branches subordinate to the company, in which the reactive power compensation was made. These calculations has been checked and reviewed. White certificates have been awarded to this company.

Table 3. Summary values from invoices and calculations.

i	days	$A_{P(i)}$ kWh	$A_{Q(i)}$ kVArh	$\tan\varphi_{(i)}$ VAr/W	$A'_{Q(i)}$ kVArh	$A_{C(i)}$ kVArh	$\delta A_{(i)}$ kWh
1	61	204862	174510	0.852	81945	92565	6480
2	60	184128	171452	0.931	73651	97801	6846
3	61	189452	185423	0.979	75781	109642	7675
4	61	208512	160214	0.768	83405	76809	5377
5	61	210245	182134	0.866	84098	98036	6863
6	61	195428	181247	0.927	78171	103076	7215
Σ	365	1192627	1054980			577929	40455

The computational example presented here concerns one point where reactive power compensation has been made. The settlement was based on 6 invoices that covered the entire calendar year. The $\tan\varphi'$ coefficient (after the compensation) was assumed to be equal to the contract value, that is 0.4. This receiver has been connected to a low voltage network (LV2 in Fig.4). The energy equivalent of reactive power is equal: $k_{e\,min} = 0.03$, $k_{e\,max} = 0.11$. It is assumed that the energy consumption in the year in which the company is applying for white certificates will be at a similar level as in the year when meter measurements were conducted. Statements and calculations were made on the basis of invoices from a representative calendar year. The total final energy savings are as follows:

$$\delta A = 40\ 455\ kWh/year.$$

This corresponds to the value expressed in tons of the oil equivalent (20):

$$\delta A_{toe} = 3.48\ \ toe/year.$$

The electricity consumer is connected to the power grid, which is characterized by the production of electricity from renewable and non-renewable sources. In this case (according to Tab.1), w_i factor is equal to 3. According to Equation (21), the average annual primary energy savings are:

$$\delta A_p = \delta A \cdot w_i = 121\ 365\ kWh/year,$$

in *toe*: $\quad \delta A_{p\,toe} = \delta A_{toe} \cdot w_i = 10.44\ toe/year.$

As a result of the foreseen reactive power compensation, the threshold of 10 *toe* will be exceeded, so the entity can apply for white certificates.

The CO_2 emission factor for power plants and combined heat and power plants that use bituminous coal is as follows [5]:

$$we_{CO2} = 93.8\ kg/GJ.$$

The reduction of CO_2 emissions per year (22) is:

$$\Delta E_{CO2} = \delta A_p \cdot 3.6 \cdot 10^{-3} \cdot we_{CO_2} = 40.98\ tons_{CO_2}/year.$$

4 Discussion and Conclusions

The proposed two methods of determining the savings of active energy due to the compensation of reactive power have some faults and difficulties. Where the network topology is simple and the measured power values are known at each point in the network, the detailed analytical method may be used. In other cases, a estimation method can be used, which requires the knowledge of the values of k_e factor: the energy equivalent of reactive power. The disadvantage of this method is the inaccuracy of calculations, which is dependent from the error in the determination of k_e coefficient, but in economic calculations, which the purpose is to know the approximate value of the power saved, such a calculation is acceptable.

When considering a recipient of electricity with a large number of divisions scattered in many different places in the power system, so far no computational energy audit has been developed. In these cases, no electricity audits were made. The author of this article has consulted experts from several countries in Europe. Only Italians performed such audits, but in calculations they limited themselves to analysing the last segment of the electricity network - between the meter and the receiver.

By using the estimation method, the author performed two power audits in 2014 and 2016. The calculations concerned one of Polish companies dealing with the sale of automotive fuels. Both audits have passed a positive review in the Ministry and have been granted white certificates.

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