Loading three phased transformer following the quadera
gy

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Abstract. In this work, the authors propose a simple and fast method to establish the minimal real power for loading a three phased transformer of a specific power, such that power factor does not drop below a previously defined value. The method can be applied to transformers that are placed between a consumer’s metering point and the electric power distribution network. In this situation, the billing energy and quadera
gy include the transformer energy and quadera
gy losses. This method establishes the moment where, due to low energy consumption, the transformer should be replaced with a lower power one, which still ensures the necessary energy for the consumers behind it. Our analysis has been done on a 100 kVA, an 80 KVA, and a 16 kVA transformer. Applying this method expedites the process of establishing the energy and the power factor where a transformer should be replaced by a lower power transformer, such that the power factor stays in acceptable ranges.

1. Introduction
Many economical units are connected to the electrical distribution network through 20 kV/0.4 kV transformers of various powers. As the electric load of these consumers varies irregularly, small energy loads appear, with negative technical effects (noise) [1] such that the associated quadera
gy causes a power factor below 0.65, having a negative impact on the consumed energy billing.

Most of the time, the metering point differs from the connection to the 20 kV energy network point, which is considered to be the billing point. In this situation, the specific legislation [2] establishes a methodology to compute the transformer energy and quadera
gy losses. Depending on the transformer’s power, the bill will include energy and quadera
gy corrections, which, together with the metered energy, will make up the total sum for a given time period (usually a month).

When the metering point is not the same as the billing point [3], for a period of time, even though no energy consumption is registered, the energy bills include high energy and inductive quadera
gy correction values, as can be observed in Figure 1.

2. Theoretical Considerations on Correction Computations
According to Directive 24/2006 of the Romanian Energy Regulatory Authority (ANRE), when the metering point (PM) is different from the billing point (BP), and the meter can measure neither hourly energy consumption, nor the electric energy load curve, we have the following losses:

- Constant energy losses, which can be:
  - Electric energy $\Delta E_{ac}$:
\[ \Delta E_{ac} = P_0 \cdot T_f \quad [\text{kWh}] \]  

- Electric quadergy \( \Delta E_{re} \):

\[ \Delta E_{re} = \left( \frac{i_0 \%}{100} \right) \cdot S_n \cdot T_f \quad [\text{kVARh}] \]  

where \( P_0 [\text{kW}] \) stand for the transformer losses in the no-load operation state, \( T_f [\text{h}] \) is the time period for which the transformer is live, \( i_0 \% \) is the no-load operation current, and \( S_n [\text{kVA}] \) is the transformer’s rated apparent output. For a consumer functioning without human staff, or for an automation equipment, we consider \( T_f 24 \text{ h} \) (one day).

b. Variable energy losses, which can be:

- Electric energy \( \Delta E_{av} \):

\[ \Delta E_{av} = P_{sc} \cdot \left( \frac{S_m}{S_n} \right)^2 \cdot \tau \quad [\text{kWh}] \]  

- Electric quadergy \( \Delta E_{rv} \):

\[ \Delta E_{rv} = \left( \frac{u_{sc} \%}{100} \right) \cdot \left( \frac{S_m}{S_n} \right)^2 \cdot S_n \cdot \tau \quad [\text{kVARh}] \]  

where \( P_{sc} [\text{kW}] \) stand for the transformer losses in the short-circuit operation state, \( S_m [\text{kVA}] \) is the maximum apparent power, \( u_{sc} \% \) is the short-circuit voltage, and \( \tau [\text{h}] \) is the period on which the losses are computed, whose value is established by ANRE, depending on the number of functioning hours. During the short-circuit operation, even when very short, additional energy losses happen due to the high current values [4].

| Specification             | MU | Const | Read index 31.03.2018 | Read index 01.03.2018 | Quantity | Corrections BP ≠ MP | Other corrections | Measured quantity |
|---------------------------|----|-------|------------------------|------------------------|----------|---------------------|-------------------|------------------|
| Electric Energy           | kWh| 1     | 1685.8                 | 1685.8                 | 0        | 63                  | -                 | 63               |
| Inductive quadergy        | kVARh| 1     | 40.231                 | 40.231                 | 0        | 476                 | -                 | 476              |
| Capacitive quadergy       | kVARh| 1     | 57.493                 | 55.314                 | 2        | -                   | -                 | 2                |

**Table:**

| PF ≥ 0.90            | 0     | 0     |
| 0.65 ≤ PF < 0.90    | 0     | 0     |
| PF < 0.65           | 445   | 0     |

**Figure 1.** Energy corrections when the metered energies are zero

The consumer’s power factor, \( \phi_m \), depends on the energy \( E_{am} \) and on the quadergy \( E_{rm} \) measured at the consumer location:

\[ \cos \phi_m = \frac{1}{\sqrt{1 + \left( \frac{E_{rm}}{E_{am}} \right)^2}} \]
To find the maximum apparent output, $S_m$, we must compute the maximum real output, $P_m$:

$$S_m = \frac{P_m}{\cos \phi_m} = \frac{E_a}{\cos \phi_m \cdot T_{sm}} \text{ [kVA]}$$

(6)

where $T_{sm}$ is the duration use of the peak load whose value is established, depending on the number of operating hours, by the ANRE.

The energy and quadrage energy technical losses, $\Delta E_a$ and $\Delta E_r$, show on the bills as corrections, are determined with the following equations:

$$\Delta E_a = \Delta E_{ac} + \Delta E_{av} \text{ [kWh]}$$

(7)

$$\Delta E_r = \Delta E_{rc} + \Delta E_{rv} \text{ [kVARh]}$$

(8)

All transformer losses can be determined already in the transformer design phase, during simulations of various regimes transformer operations [5-8].

The energy and quadrage energy which are used to compute the energy consumption at the billing point are computed using the following equations:

$$E_a = E_{am} + \Delta E_a \text{ [kWh]}$$

(9)

$$E_r = E_{rm} + \Delta E_r \text{ [kVARh]}$$

(10)

The lagging power factor at the delimitation point (including the transformer) is computed by:

$$\cos \phi = \sqrt{\frac{1}{1 + t g^2 \phi}} = \sqrt{\frac{1}{1 + \left(\frac{E_r}{E_a}\right)^2}}$$

(11)

According the ANRE directives [2], [9] consumers pay the total capacitive quadrage, and for the inductive quadrage the consumers pay only the quantity that exceeds the power factor limit value at the delimiting point. The lagging power factor limit is 0.92 and the capacitive power factor limit is 1. When the consumer effects a power factor lower than 0.65, he will pay the rate difference between the recorded quadrage value and the value corresponding to the power factor limit value, multiplied by three. For lagging power factor values between 0.92÷0.65 the quadrage price rate is the one fixed by ANRE.

3. Case Study

In this work we analyse an industrial consumer where the metering point is different from the billing point, while at the consumer point an hourly time counter and a transformer with the following nominal values are installed:

- Nominal power $S_n = 100$ kVA;
- Primary rated voltage $U_{1n} = 20$ kV;
- Secondary rated voltage $U_{2n} = 0.4$ kV;
- Primary winding current flow $I_{1n} = 20$ A;
- Secondary winding current flow $I_{2n} = 0.4$ A.

According to ANRE directives [10] for this transformer type we have the following technical parameter values defined:

- No-load operation transformer losses $P_0 = 0.6$ kW;
- Short-circuit operation transformer losses $P_{sc} = 2.76$ kW;
- No-load operation current $I_{0%} = 3.3$;
- Short-circuit voltage $u_{sc%} = 4$;
- Loss computation time for a monthly continuous operation with 24 hours per day, $\tau = 203$;
Peak load use duration for a monthly continuous operation with 24 hours per day, $T_{sm} = 430$.

Table 1 presents the energy and quadergy values we measured, as well as their corrections according to the energy distribution provider bills.

**Table 1.** Power factor, energy and quadergy values, correction factors for 2008

| Month    | $E_{am}$ [kWh] | $\Delta E_a$ [kWh] | $E_{ar}$ [kVARh] | $\Delta E_r$ [kVARh] | $\cos \phi$ |
|----------|----------------|---------------------|------------------|----------------------|-------------|
| Jan.2008 | 4268           | 451                 | 301              | 2538                 | 0.857       |
| Feb.2008 | 2590           | 420                 | 186              | 2370                 | 0.762       |
| Mar.2008 | 2385           | 448                 | 263              | 2532                 | 0.712       |
| Apr.2008 | 2364           | 434                 | 150              | 2451                 | 0.732       |
| May.2008 | 2576           | 449                 | 406              | 2533                 | 0.717       |
| Jun.2008 | 1842           | 412                 | 466              | 2450                 | 0.612       |
| Jul.2008 | 2504           | 448                 | 913              | 2533                 | 0.651       |
| Aug.2008 | 2228           | 448                 | 801              | 2532                 | 0.626       |
| Sep.2008 | 2086           | 433                 | 872              | 2450                 | 0.604       |
| Oct.2008 | 2130           | 447                 | 513              | 2532                 | 0.646       |
| Nov.2008 | 2060           | 434                 | 507              | 2451                 | 0.731       |
| Dec.2008 | 1962           | 448                 | 309              | 2531                 | 0.647       |

Figure 2 shows the billed energy and quadergy variations and the power factor variations for 2008.

![Diagram](attachment:image.png)

**Figure 2.** Billed energy and quadergy variations, power factors variations for year 2008

The power factor computed using equation (11) is scaled by a factor of 1,000 in order to represent it on the same coordinate system. On the same figure, scaled by a factor of 1,000 we show the 0.65 power factor where the quadergy is billed three times the regulated value.

We immediately notice that for June, August, September, October, and December the power factor value was below 0.65, which led to additional electricity costs.
To reduce these costs, the transformer was replaced with a 80 kVA apparent output transformer.

The measured energy and quadergy, as well as their corrections given by the electricity distribution provider are shown in Table 2.

### Table 2. Power factor, energy and quadergy values, correction factors for 2012

| Month   | \(E_{am}\) [kWh] | \(\Delta E_a\) [kWh] | \(E_{ar}\) [kVARh] | \(\Delta E_r\) [kVARh] | Cos \(\phi\) |
|---------|------------------|----------------------|-----------------|----------------------|-------------|
| Jan.2012| 1859             | 0                    | 69              | 0                    | 0.999       |
| Feb.2012| 2092             | 261                  | 63              | 1842                 | 0.777       |
| Mar.2012| 1900             | 278                  | 187             | 1968                 | 0.711       |
| Apr.2012| 840              | 266                  | 125             | 1902                 | 0.479       |
| May.2012| 641              | 276                  | 170             | 1965                 | 0.395       |
| Jun.2012| 544              | 267                  | 214             | 1901                 | 0.358       |
| Jul.2012| 621              | 276                  | 248             | 1965                 | 0.376       |
| Aug.2012| 695              | 276                  | 289             | 1965                 | 0.396       |
| Sep.2012| 688              | 267                  | 188             | 1901                 | 0.416       |
| Oct.2012| 934              | 276                  | 81              | 1965                 | 0.509       |
| Nov.2012| 938              | 267                  | 27              | 1902                 | 0.530       |
| Dec.2012| 1350             | 276                  | 25              | 1966                 | 0.633       |

Figure 3 shows the energy and quadergy variations and the power factor variations for year 2012.

![Energy and Quadergy Variations](image)

**Figure 3.** Billed energy and quadergy variations, power factors variations for year 2012

Using the data from Tables 1 and 2, and observing Figures 1 and 3, using equation (11), we obtain that for a 744 operation hours per month, to have a power factor higher than 0.65, the consumer’s average power must not go below 3% of the 100 kVA transformer’s nominal power, and not below 2.6% of the 80 kVA transformer’s nominal power.

Beginning with 01.01.2017, with new ANRE directive [11] it was regulated that the 0.92 neutral power factor becomes the limit power factor, with a value of 0.90. This allowed the non-billing of inductive and capacitive reactive power up to a value of 0.90.

Analysing Figure 3 we note that in March 2012 the power factor is higher than 0.65, which followed a drastic decrease consumer energy use. By replacing the 80 kVA transformer by a 16 kVA transformer, at the same time when the energy consumer is suspended, the energy corrections are...
significant, considering the computed losses. For this type of transformer [10] we have the following technical parameters:

- No-load operation transformer losses $P_0 = 0.065$ kW;
- Short-circuit operation transformer losses $P_{sc} = 0.465$ kW;
- No-load operation current $i_0\% = 4$;
- Short-circuit voltage $u_{sc}\% = 4$.

Table 3 presents the measured energy and quadergy values, as well the corresponding corrections as they were calculated established by the energy distribution provider, as shown on the bill (Figure 1).

| Month     | $E_{\text{am}}$ [kWh] | $\Delta E_a$ [kWh] | $E_{\text{ar}}$ [kVARh] | $\Delta E_r$ [kVARh] | $\cos \varphi$ |
|-----------|------------------------|--------------------|--------------------------|-----------------------|----------------|
| Feb.2018  | 0                      | 57                 | 2                        | 430                   | 0.131          |
| Mar.2018  | 0                      | 63                 | 2                        | 476                   | 0.131          |
| April 2018| 0                      | 61                 | 2                        | 461                   | 0.131          |

Figure 4 shows the billed energy and quadergy variations and the power factor variations for February, March and April, 2018, when the consumer is using the 16 kVA transformer.

4. Conclusions

Analysing the data on the energy bills as well as the corresponding loss calculations we have determined the moment when, due to no energy consumption, a decision about a transformer replacement or about an energy contract change should be made.

The use of this method allows obtaining a quick, solid fact basis to show the energy distributor such that new, equally advantageous contracts between partners can be closed.

For a 100 kVA transformer, such that the power factor is higher than 0.65, the average consumer power must not drop below 3% of the transformer’s nominal power. For the 80 kVA transformer, the consumer power must not drop below 2.6%.

We found that, although the original transformer has been replaced with a lower power one (16 kVA) for a no energy consumption the applied corrections are still rather high.
Looking at Figure 4 we see that for no energy nor quadergy consumption, in a three days interval, in two consecutive calendar months, the energy corrections are almost double. The cause of this must be spelled out and clarified by the energy distributor.

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