Algorithms for Precise Anticipation of Reactive Energy Savings in Compensated Power Systems

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Abstract – **This paper presents some problems that can appear during the precise determination of exact values of reactive energy savings in compensated power systems, as well as specific methods used for their solutions. Final results of the research, contained in this paper are obtained from a comparative analysis of results of reactive energy consumption monitoring, registered by two different measuring devices: one commercial energy meter and one smart measuring device that works as a controller of the accuracy of mentioned energy meter. Those measurements are performed at one customer of electrical energy, where compensation system has already been implemented. Knowledge of the exact values of energy savings is an important aspect of the ESCO concept and therefore algorithms presented in this paper, could have high importance in energy efficiency.**

Keywords – **Algorithms, reactive power, energy savings, compensated system, energy efficiency.**

I. Introduction

The transfer of reactive power through transmission and distribution lines and transformers has many disadvantages with respect to the power system construction and operation. Active losses are increased and a higher cross-section of lines is sometimes required. Reactive losses are increased, as well. Furthermore, the voltage drops in the system are increased, resulting to the need to choose a higher regulation range of tap-changers for the transformers. Therefore, consumed reactive energy is charged. Power distribution companies use different billing methods: pricing based on reactive energy, based on apparent energy and different amounts for low and high tariffs.

Energy efficiency and power quality over past decades became one of the most important global issues. In power distribution networks one of the most common improvement measure is reactive power compensation. There are several methods and types of compensation in practice, but this paper considers use and effects of the simplest shunt type compensation.

For ESCO model financing of energy efficiency projects, the main stuff based in every project is predicting of total available budget in correlation with potentially realized savings [1].

Power utility companies take registered values from the power utility meters, as elements in the preparation of bills for electricity. However, during the anticipation of realized savings, according to ESCO concept, it is necessary to have information about monthly consumption of reactive energy in the certain consumer system, as well as values of uncompensated reactive energy in the same system, after the implementation of system for compensation. The great importance of this information is in the evaluation and subsequent precise determination of realized savings and expressing of their economic effects.

II. Formulation of the Problem

The largest number of analysis was based on collected data, recorded by systems for the electrical energy consumption monitoring. These systems have already been placed in several industrial facilities, which are in possession of one customer and each of those systems consists two parts used for different purposes. One part of smart measuring device is used for registering all current values of electrical parameters at the place of implementation: phase and line currents and voltages, frequency, active, reactive and rated power, consumed active and reactive electrical energy, as well as calculation of their effective values. Another part of this device is used to record measured results and to control electrical energy consumption [2, 3]. Mentioned industrial facilities can be classified to the bakery industry.

In this paper, measurements in two different facilities are going to be analysed. At both measuring locations, systems for shunt compensation have been implemented. The main goal in this analysis is precise calculation of reactive electrical energy savings at both places, as well as the calculation of total reactive electrical energy, that would be taken from the electrical energy system (EES), if the compensation system wasn't implemented. The main difference between these measuring points is the order of placing utility energy meter, smart control measuring device and capacitor battery to the customer's electrical supplying. In both cases, some problems can appear during specified calculations. In order to skip these problems certain algorithms were used.

At the first measuring point utility energy meter, smart measuring device and shunt compensation system are placed in order, shown at Fig. 1. In this case utility energy meter measures the value of uncompensated reactive energy while control measuring device registers the value of total consumed reactive energy.

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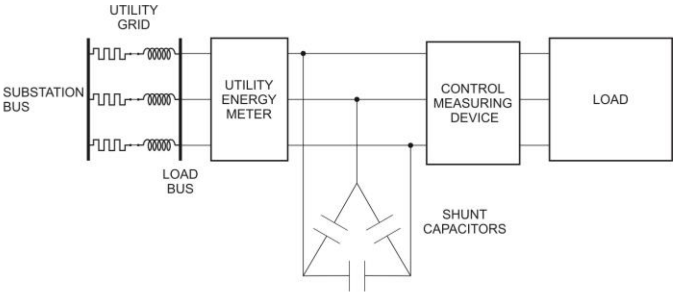

Fig. 1. System for measuring and reactive power compensation implemented at the first location

Time period for which calculations are going to be done is one month in accordance with period for which electricity supply companies deliver bills for consumed energy. Reactive electrical energy that can be saved using the shunt type compensation is:

$$Ec = Q_{bat_n} \cdot t \tag{1}$$

where Q_{bat_n} is rated value of battery capacity, and t is period during which compensation system works. For this calculation, this period is one month (720 hours). If the proper operation of utility energy meter should be checked, it is possible to do it by simply adding the value that is registered by utility power meter and reactive energy saved by compensation system and compare with the value registered by smart measuring device. If the utility meter operates properly, these two values will be approximates.

This method can be applied only for the rough estimate where the only important thing is proper operation of utility energy meter. In all other calculations, it is necessary to take into the account dependence of reactive power compensated by capacitor battery on quality of voltage in electrical grid. This dependence is given as:

$$Q_{bat} = Q_{bat,n} \cdot \left(\frac{U_{mean}}{U_{bat_n}} \right)^2 \tag{2}$$

where U_{mean} is mean value of the line voltage for each individual measurement, U_{bat_n} is voltage for battery's optimal operation and Q_{bat} is real value of reactive power saved by compensation system for each individual measurement, as well. In attention of precise calculation of reactive energy savings and real value of consumed reactive energy before compensation, specified algorithms are used.

Measuring of electrical parameters by smart measuring device was performed at intervals of ten seconds during the period of six months. Results of those measurements were stored as .b files. In the beginning, it is necessary to import all measuring results to one of programmable packages. Parameters that have the special importance for following calculation are line voltages and total value of reactive power, given as a sum of phase reactive powers. The next step is to calculate mean value of the line voltage that affects calculation of real value of reactive power saved by compensation system. Then, real value of capacitor battery should be determined by Eq. (2). This process should be done for each individual measurement performed during the considered period. Now, it is possible to calculate uncompensated reactive power by subtracting real value of compensated power from the value of reactive power registered by smart measuring device. This step should be done for each individual measurement, as well. The next step is to calculate total uncompensated reactive power during the period of one month as a sum of all real values of uncompensated reactive power for the same month, determined in the previous step. Finally, it is possible to calculate total uncompensated energy taken from EES as a product of total uncompensated power in one month and number of hours in the consider month (720). Analogously, total reactive energy taken from the grid during the same month can be determined as a product of total reactive power (sum of all individual values of reactive power registered by smart measuring device during the period of one month) and number of hours in the month. Real value of energy savings can be determined here by subtracting the value of uncompensated reactive energy from the value of total reactive energy taken from the EES.

In order to check utility energy meter's proper operation, the value of uncompensated reactive energy, calculated by described algorithm, should be compared with the value registered by utility power meter.

One of the initial ideas, on which is based ESCO concept is knowing the real value of reactive energy savings. Other advantages obtained from this algorithm are conversance of all electrical parameters, which are describing the quality of voltage and electrical energy delivered to the customer.

At the second measuring point utility energy meter, smart measuring device and shunt compensation system are placed in order, shown at Fig. 2.

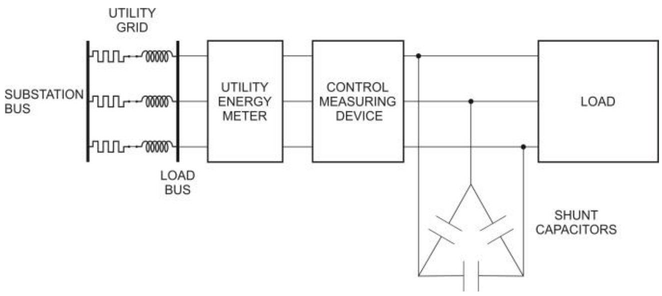

Fig. 2. System for measuring and reactive power compensation implemented at the second location

In this case both measuring devices register the value of uncompensated reactive energy. The parameter that should be determined is value of compensated reactive power, as a function of the line voltage. It is also important to calculate the value of reactive energy that would be taken from the electrical energy system in a case that compensation system wasn't installed.

As in the previous case, it is necessary to take into the account the dependence of reactive power on a quality of voltage, given by Eq. (2). As at the first measuring location, measuring of electrical parameters by smart measuring device was performed at intervals of ten seconds during the period of six months. Results are also stored as .b files. The process of importing the recorded data and procedure for determining mean value of line voltage and real value of reactive power saved by compensation system is absolutely the same as in the first model. Parameters that should be determined here are values of total reactive power that customer's system would take from the grid in the case of absence of system for shunt compensation, for each individual measurement during the considered period. It can be done by adding the real value of compensated power to the value registered by smart measuring device. Therefore, total reactive power taken from the EES during the one month should be determined as a sum of values of total reactive power for each individual measurements which are performed during the same month. Finally, the overall reactive energy that could be taken from the EES, in the period of one month at this measuring location could be determined as a product of total reactive power and number of hours in the month.

This calculation is applicable for customers, where it is not possible to set smart measuring device close to the place of customer's supplying. Electrical parameters calculated by this algorithm have a great importance for electrical energy consumption planning that represents the basis for "smart grid" systems development [4].

III. RESULTS AND DISCUSSION

Algorithms presented at previous chapter were applied to data gained from monitoring by smart measuring devices installed at two compensated industrial systems. At both measuring locations parameters of electrical energy consumption were being monitored during the period of six months. Algorithm used for measurements at first measuring location gave results shown in Table I.

TABLE I

Months	REBC* [kvarh]	REAC – SMD** [kvarh]	REAC – UEM*** [kvarh]
January	3184.7	-3110.7	1262
February	3220.7	-2488.5	969
March	3592	-2720.0	1055
April	3465.9	-2721.4	1187
May	3840.8	-2529.9	1034
June	4343.9	-1795.2	990

* Reactive energy before compensation registered by smart measuring device
** Reactive energy after compensation – calculated by first algorithm
*** Reactive energy after compensation registered by utility energy meter

After comparison of values of uncompensated reactive energy registered by utility energy meter and obtained by presented algorithm, large differences between them can be observed. Calculated values of uncompensated reactive energy by the first algorithm are smaller than zero and indicate deep system's overcompensation. On the other side, utility energy meter registered large positive values of uncompensated reactive energy. Those results indicate to incorrect operation of utility energy meter and its replacement.

Diagram of the power supply line voltage for one of considered months is shown in Fig. 3. Diagrams of reactive power savings and reactive power before and after using shunt compensation are shown in Fig. 4.

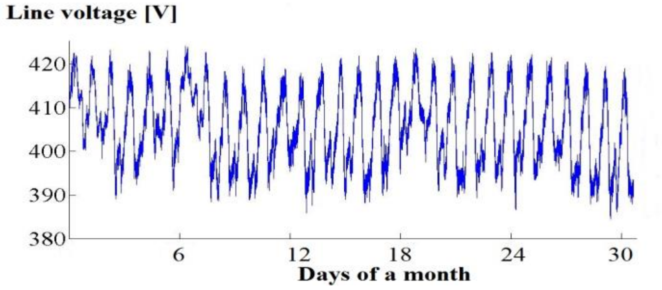

Fig. 3. Monthly diagram of power supply line voltage changes at first measuring location

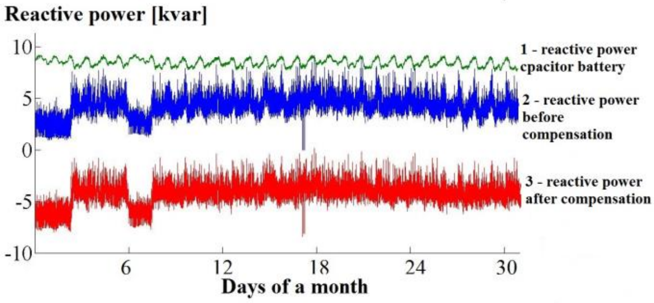

Fig. 4. Monthly diagrams of reactive power at first measuring location

Diagrams in Fig 3. and Fig. 4 show how in practice power of capacitor battery depends on the line voltage changes: with higher mean value of line voltage, compensated reactive power is also higher. It is also possible to notice that during the whole month, power of the capacitor battery is higher that the reactive power taken from the EES that is a proof of great overcompensation at this location.

Algorithm applied to measurements done at second customer's system obtained results shown in Table II.

TABLE II

Months	REBC* [kvarh]	REAC – SMD** [kvarh]	REAC– UEM*** [kvarh]
January	2062	-2479.4	0
February	1924	-2246.2	0
March	2100	-2524.4	0
April	2265	-2223.8	0
May	2509	-2121.6	0
June	2735	-1762.0	0

* Reactive energy before compensation – calculated by second algorithm
** Reactive energy after compensation registered by smart measuring device
*** Reactive energy after compensation registered by utility energy meter

After comparison of values of uncompensated reactive energy measured by smart measuring device and utility energy meter it can be concluded their deviation. Values registered by smart measuring device are negative as opposed to values registered by utility energy meter (zeros for all six months). This difference is result of utility energy meter's constructional impossibility of measuring in all four quadrants – it can't register values of reactive power smaller than zero. Instead of negative values it records zeros. Anyway, utility energy meter's proper operation is not brought to the suspicion at this measuring location.

On the other side, at both measuring locations great overcompensation is present. This is really positive impact to EES, because a large amount of reactive electrical energy was generated to the grid. However, this situation is not fair to the customer, because he doesn't receive any fee for mentioned reactive energy's generation, while his costs for compensation system could be lower if he replaced this system by another one with the capacitor battery of less rated power.

Anyway, main goal achieved by application of this algorithm to results of measurements at this location is overall electrical energy that could be taken from EES in a case shunt compensation's absence. This data is really important for consumption planning that represents one of main ideas of ESCO concept.

Diagram of power supply line voltage for one of considered months at second measuring point is shown in Fig. 5. Diagrams of reactive power savings, reactive power before and after using system of compensation at the same point are shown in Fig. 6.

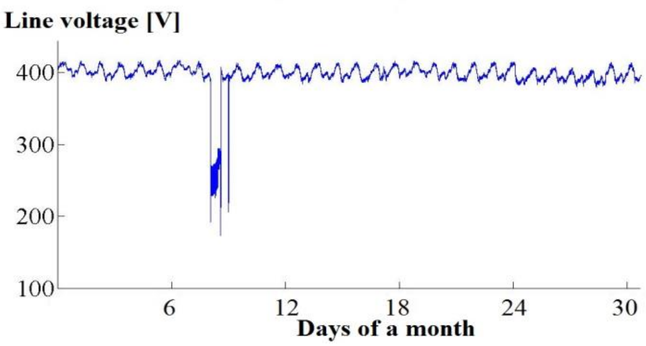

Fig. 5. Monthly diagram of power supply line voltage changes at second measuring location

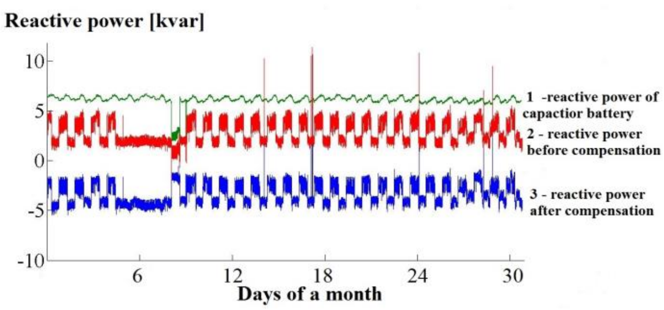

Fig. 6. Monthly diagrams of reactive power at second measuring location

Voltage drop shown in a diagram in Fig. 5. is followed with the lower value of reactive power that is compensated by shunt capacitors, presented in Fig 6. Greater reactive power of capacitor battery than a reactive power taken from EES represents overcompensation at customer's system. A fact that desired results could be achieved with the battery of less rated power had been really important for the customer. At both measuring locations, existing capacitor batteries were replaced with the batteries of less nominal power and in this way customer costs were reduced and these industrial systems became more energy efficient.

IV. Conclusion

Precise anticipation of reactive energy savings in shunt compensated power systems can be performed by using of presented algorithms. Naturally, the main condition for their applying is presence of measuring results, gained by smart measuring device for electrical parameters. Knowledge of energy savings is base for energy efficiency improvement and knowledge of electrical parameters in EES represents the first step in successful monitoring and controlling of power distribution grid.

Described algorithms were applied to the simplest systems for reactive power compensation. Further researches in this area could include other types of compensation systems, such as dynamic system, where automatic control for its optimal operation is installed. In these installations optimal capacitors batteries switching on and off should be included, achieving its longer lifetime and reducing of the customer's costs.

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