Proactive compensation of electric power imbalance in day-ahead market

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Abstract. The precise planning of production and demand schedules is essential for the stability of the energy system. For this purpose, various economic incentives have been developed and implemented that encourage accurate adherence to the pre-registered schedules. In order to respond to the strictly following of the schedules a proactive compensation of electric power imbalance in day-ahead market is suggested. An original methodology for parameter estimation of the Imbalance Compensation System is proposed and experimental results are reported.

Key Words. electric power, imbalance compensation, day-ahead market

1. Introduction
One of the main features of electricity is the inability to store it, which requires that the balance between the generated and the consumed power has to be maintained at a constant frequency of alternating voltage. When this balance is disturbed, the frequency of the voltage [1] changes immediately. The operational planning, management and control of the electricity system (ES) is carried out by the Transmission System Operator and the operators of each of the electricity distribution grids [2]. The main tasks of the Transmission System Operator related to the real-time control of production capacity is to maintain the balance between consumption and production of electric power [3].

The electricity market in Bulgaria is in a process of gradual liberalization, which started in 2004 and continues to this day. It consists of two segments - a regulated price segment and a freely negotiated price segment, or so-called free market. In the regulated segment, all prices and charges are set by the Energy and Water Regulatory Commission (EWRC), and consumers are served by the Electricity Companies on a territorial basis. Currently this segment includes domestic consumers and business customers connected to low voltage distribution networks. In the free market segment, customers can choose their electricity supplier regardless of their geographical location by paying fixed network transmission charges, as defined by EWRC [4]. According to [2, 5] contracts at freely negotiated prices are concluded between:

• Electricity producers;
• Electricity traders;
• Consumers registered on the free market.
  The precise planning of production and demand schedules is essential for the stability of the energy system. For this purpose, various economic incentives have been developed and implemented that encourage accurate adherence to the pre-registered schedules.

In the free electricity market, there are rules for calculating the price of imbalances between the pre-registered schedule and the measured real values of energy provided by producers or consumed by consumers. Settlement periods are defined as distinct one hour time frames for which the imbalance of the responsible parties is calculated.

The pre-registered schedule represents the quantities agreed between trading participants before the actual delivery day. Measured real values are the values reported by the measuring devices of energy producers or consumers. The imbalances are determined on the basis of measured values for production or consumption [L-5]. The value of the amount paid by the free market participant can be determined by the following expression:

\[
VPE = VCE + V_{SuE} + V_{ShE} =
\]

where
- \(VPE\) is the Value of the Paid Energy
- \(VCE\) is the Value of the Contracted Energy;
- \(V_{SuE}\) - the Value of the Surplus Energy;
- \(V_{ShE}\) - the Value of the Shortage Energy;

At the end of each settlement, the imbalance should be kept to a minimum. It does not matter how the consumption has changed over time, the total consumption for settlement is essential. With active management of consumed energy during each settlement period, the imbalance can be minimized.

2. Imbalance Compensation System

The use of an Imbalance Compensation System (ICS) aims to keep the consumer's actual load schedule as close as possible to the contracted one.

The error can be compensated by:

• Switching on and off non-basic electric consumer devices;
• Accumulation and delivery of electricity through an energy storage system (ESS).

When compensating the imbalance error, the consumption is controlled by switching on and off non-essential consumers. If the actions taken are not sufficient, the available ESS capacity can be used.

Various factors can influence the error compensation process. This requires a preliminary analysis of these impacts. The results of the analysis will determine the necessary conditions and parameters under which the error will be compensated by using the ICS.

Some of the major factors that have a significant influence on the work of the ICS have been formulated and substantiated.

2.1. Analysis of the imbalances obtained

The prediction error for each settlement is determined by the expression:
\[ \Delta E(t) = E_{\text{реално}}(t) - E_{\text{прогн}}(t) \]

where \( E_{\text{реално}}(t) \) denotes the actual electricity consumption for the settlement, [kWh], and \( E_{\text{прогн}}(t) \) indicates the contracted electricity consumption for the settlement, [kWh].

If \( \Delta E(t) > 0 \) there is a shortage and in this case, non-essential consumers should be turned off to compensate the imbalance.

If \( \Delta E(t) < 0 \) a surplus is obtained and in this case, non-essential consumers must be turned on to utilize unused energy.

Consumption, and hence the resulting imbalance of one consumer, can be influenced by different random processes that cannot be predicted at the stage of forecasting.

Experimental data set is required to evaluate forecasting errors. An error histogram is constructed to initially visualize the resulting forecast errors.

In order to determine the appropriate power capacity of the Imbalance Compensation System, a statistical analysis of the errors must be carried out. The result of this will be the basis for determining the parameters of the Imbalance Compensation System.

For statistical analysis, it is recommended to use distribution-free (non-parametric) methods [7-9]. Wilcoxon signed-rank test was used in which the hypothesis was tested by formulating a one-sided criterion.

### 2.2 Determining the optimal capacity of the energy storage system

An important factor for minimization of the prediction error is the correct power selection of the consumers participating in the ESS. Choosing a smaller capacity may not produce the desired results and, at a higher capacity, there may be significant start-up investments that are ultimately not justified by the results obtained.

Our analyzes indicate that it is recommended that the power capacity of the ESS has to be at least three times the statistical estimate of the imbalance values obtained. This maximum power capacity must be divided into separate steps or levels. We recommend that this number be no less than eight levels.

### 2.3 Analyse the length of time interval for active error compensation

The main purpose of the ESS is to make the error at the end of each trading period (settlement) as small as possible. Therefore, the following two approaches are proposed:

- Compensation throughout the settlement period;
- Compensation only in the last quarter of settlement (from 45-th to 60-th minutes).

When compensation is made throughout the whole settlement, the ESS monitors continuously (in real time) the error between the real and the agreed value of consumption. If necessary, it switch on or switch off the non-core consumers.

For compensation in the last quarter of each settlement, the approach is as follows. The reference value of consumption in the time \( t \) (45<\( t <60 \)) is:

\[ E_{\text{ref}}(t) = \frac{t}{60} E_{\text{contracted}} \] (3)

And the calculated error \( \Delta E(t) \) is
\[ \Delta E(t) = E_{\text{ref}}(t) - E_{\text{measured}}(t) \] (4)

According to \( \Delta E(t) \) a control law for feedback control can be applied. A typical solution is the use of linear PID control law.

\[ P = k_P \Delta E(t) + k_I \int_0^t \Delta E(t) dt + k_D \frac{d}{dt} \Delta E(t) \] (5)

where \( P \) denotes the additional power which have to be switched on/off to compensate the error \( \Delta E(t) \).

For better results a nonlinear control law can be set. It has to take in consideration the limited control time (the time to the end of the settlement) and the limited additional power consumers which can be switched on/off.

2.4 Time delay for switching on and off the non-essential consumers in the Imbalance Compensation System

Consumption may result in short-term abrupt changes in the load schedule caused by the high-power consumers being switched on or off. These changes are random in nature and alternate between positive and negative values. If the frequency of these changes is high, it may cause extraordinary switching on and off a non-essential consumers by the ICS. The consequences of this may be the wear and tear of these facilities as a result of frequent transient start-up and shut-down processes.

This requires exploring the possibility of switching on and off with some timedelay. The timedelay will eliminate short-term peaks. The shorter the delay, the compensation becomes faster and therefore the error is smaller. But this will increase the number of switching cycles. Conversely, if the delay is greater, the compensation will be delayed and therefore the errors will be higher.

These considerations again lead us to an optimization problem for which the following system requirements are formed:

- Minimum number of commutations
- Minimum wage bill for electricity

2.5. Underutilized use of non-core users in the process of error compensation

The application of non-primary consumers for Imbalance Compensation System is related to the following features:

- Since switching them on is not triggered by the need for their use, but depends on the need of the Imbalance Compensation System, their benefits may be reduced. For this purpose, a benefit reduction factor is introduced.

- Since switching them off is not triggered by functional needs but by the need of the Imbalance Compensation System, it is possible that energy savings may be associated with some discomfort. A comfort reduction factor is introduced for this purpose.

Taking into account these peculiarities, correction coefficients are introduced which take into account the degree of real benefit of the non-core consumers’ participation in the error compensation process.

The values of the two coefficients depend on the characteristics of the non-basic consumer devices and on the tendency of the user to give priority to efficient use of energy.
3. Experimental results

For the purposes of this study, the electricity consumption of a consumer - a University building is considered. A mathematical model is used to forecast electricity consumption based on which a forecast is made for the each settlement within the next 24 hours. We will assume that the forecast consumption has been contracted with the electricity provider and there will be financial penalties for deviations between the real (measured) consumption and contracted consumption for each settlement.

To compensate the error during each settlement, the Imbalance Compensation System has been used. It has the following parameters:

- Total power capacity of 18 kW of non-essential consumers that will be switched on and off.
- The consumers are distributed in nine stages of 2 kW each.

Table 1 shows the daily cumulative errors using the Imbalance Compensation System. The daily error has two components negative (surplus) error and positive error. The results shown are averaged on the basis of 3 monthly data.

Table 1. The daily cumulative errors using the Imbalance Compensation System.

| Interval for active error compensation | Time delay (min) | Daily cumulative errors |
|----------------------------------------|------------------|-------------------------|
|                                        | -ΔE, (kWh)       | -ΔE, (%)                | +ΔE, (kWh)   | +ΔE, (%)   |
| 0 - 60 min                             | 1                | -3 461                  | -1.92%      | 3 343      | 1.86%      |
| 0 - 60 min                             | 2                | -3 651                  | -2.03%      | 3 525      | 1.96%      |
| 0 - 60 min                             | 3                | -3 811                  | -2.13%      | 3 691      | 2.06%      |
| 0 - 60 min                             | 4                | -3 951                  | -2.21%      | 3 847      | 2.15%      |
| 0 - 60 min                             | 5                | -4 079                  | -2.28%      | 3 959      | 2.21%      |
| 45 - 60 min                            | 1                | -6272                   | -3.48%      | 4 847      | 2.69%      |
| Without Imbalance Compensation System  |                  | -17 113                 | -7.60%      | 15 995     | 7.11%      |

Figure 1 shows series of experimental curves for the negative (surplus) error and positive (shortage) error depending on the power capacity [kW] of the Imbalance Compensation System at different values of the time delay.

Figure 1. Compensation for (a) negative (surplus) error and (b) positive (shortage) error depending on the capacity of the Imbalance Compensation System at different time delays.
Figure 2 shows the graphs of the change of the total amount paid depending on the capacity of the Imbalance Compensation System at different time delays. Comparison with the data in Figure 1 shows that if the share of the compensated energy error is about 3-5%, then this increased efficiency in terms of money reaches a share of 10%. This is due to the significantly higher energy prices outside the contracted schedule.

![Figure 2. Total amount paid depending on the capacity of the Imbalance Compensation System at different time delays](image)

Figure 3 shows a family of curves of the total amount criterion if we take into account the different levels of benefit reduction factor and comfort reduction factor. The graphs are also calculated in dependence of the power capacity of the Imbalance Compensation System.

![Figure 3. Total amount criterion if we take into account the different levels of (a) benefit reduction factor and (b) comfort reduction factor.](image)
4. Conclusion
The following conclusions can be drawn from the studies made by the use of non-core consumers for proactive error compensation of electric power imbalance in day-ahead market:
1. The results are better if compensation is made throughout the settlement compared to the case if only part of the settlement (e.g. the last quarter) is used to compensate the error;
2. Increasing the capacity of the Imbalance Compensation System beyond a certain value does not lead to a linear reduction of errors. Saturation trends are observed reaching the error limit;
3. The results at different switching time delays indicate that the obtained values do not differ significantly. For this reason, it can be chosen a time delay of greater value without significantly worsening its economic performance;

From the research we can conclude, the use of non-basic consumers to compensate for the error has a positive economic effect. The identified parameters and factors affecting the algorithm are key to performance and can be explored in more detail.

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