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MODEL OF ELECTRIC ENERGY CONSUMPTION CONTROL – ITS POSSIBILITIES AND RESULTS OF SIMULATION RESEARCH

Dariusz Bober, Henryk Kaproń

Keywords: power modes model, smart grids, distributed control, hierarchical control systems, smart metering and control

Summary. In the article authors present the idea of a new model of electrical energy consumer powering – the power modes model. The model is implemented in the Matlab® environment and it has been tested for the real parameters and data of one Polish power supplier of 2007 year spectrum. The proposed methods of data metering and acquisition allow for the parallelity of control process of electric energy consumption in a distributed environment of a power grid system, or a part of that system. This article extends the model description and authors research details published in [7, 8]. The first version of this work was presented at The International Multi-Conference on Complexity, Informatics and Cybernetics, which took place at 6th-9th April 2010, Orlando, Florida, USA. Thanks to the Organizers, whose the authors have asked for this possibility, this copy of the article [9] could be presented for the Energy Market journal readers.

1. INTRODUCTION

Basically, a power grid system could be presented as a hierarchical structure (fig. 1) where the node on the top is the supplier which distributes the power to the lower level of hierarchy. The nodes of that level represent e.g. the departments of the supplier, the power stations an substations, the subareas of the whole geographical area where the supplier distributes the energy. At the lowest level of the hierarchy are the energy consumers. Here is some more information:

- one node of energy consumer could represent an internal hierarchy of energy distribution grid, with similar structure to fig. 1, where the main node represents the consumer and the sub nodes are his production objects and the electrical equipment on the lowest level.

- and on the other side the whole structure of the supplier (fig. 1) could be a subsystem of the global power system, and then the main node of the hierarchy (fig. 1) becomes a node on the lowest level of the global hierarchy – the transparency of line-node functionality.

It is important that the following be true on each node of each level of the hierarchy [11]:

\[ P_{S}^{(\text{level} - 0)} = f(x, \Sigma P_{D}^{(\text{level} - 1)}). \quad (1) \]

The power supply \( P_{S} \) ability (1) of a node on level 0 is function \( f \) of sub nodes power demand summary and it is also determined by a technical condition \( x \) of power grid infrastructure. On the other hand, the power demand \( P_{D} \) of one node of level -1 depends of the power supply of its supplier and its neighbours – the other nodes of level -1. So the main node needs to order/generate such sufficient power as its sub nodes demand. On the other side the sub nodes of the node cannot demand more power that the node is able to supply. In this situation it is necessary to introduce some power supply limitation. The sub nodes ought to calculate the risk of the lack of electricity situations.

![Fig. 1.](image_url) The hierarchical structure of electric energy distribution process – power system. The marked line-nodes present the transparency of node functions – a node of the lowest lever - a consumer - becomes the supplier in its internal distribution grid.

The cost of lack of electricity [10, 20] and the newest blackouts history [12, 15] necessitate the need for change and to develop a new, better solutions. The power modes model - presented in the next chapter – is helpful for the solution researching.

2. REMODELLING OF THE ELECTRIC ENERGY CONSUMPTION STRUCTURE

Based on the research [2, 3] of the households consumers’ preferences and decisions of energy consumption limitation in the situations of power deficit, it is advantageous to remodel the power consumption model.

The consumers are interested in taking active part in the power system balancing process. The consumers want to have a choice which of their electrical equipment they can turn off in a situation of power deficit and in the same way they will back the power
to the system (by demand decreasing) and which ones are so important to their owners so they have to be powered, even for the electric energy cost increasing. The practice of rotating switching off all parts of the distribution grid [11, 16] does not give them a choice. For some period they are in a local blackout situation, with no electricity, no elevators, no air-conditioning, no water, and no communications [10]. The power modes model offers some solution.

2.1. Power modes model

The details of the power modes model are published in [3, 4], here the main idea of the model is presented. Let us imagine that there are technical and financial resources for implementation of a highly intelligent metering and control system of power consumption. The system provides online control of the all consumers electrical equipment and decides (of course after the consumers’ parameterization) which equipment should be turned on and which should be turned off – the global intelligent grid of total control.

Although it is imaginary, there is no necessity for control of each individual piece of electrical equipment, there is no necessity for such a detailed control. The research [3] shows that the consumers needs are divided into some typical groups: there is some electrical equipment which play very important functions for their owners and that functions are so critical that they decide to pay more for the electricity to keep them working, even in a situation of a power deficit. This fact was also observed by J. Paska “… in some times of a day consumers are ready to pay more for the reliability than in other ones” [20]. If encouraged economically, the consumers are ready to stop using some of their equipment functions for some time. There is a group of electrical equipment in each household which does not play very important functions for their owners (the consumers) and, if a power deficit situation occurs, they are ready to turn them off [3]. The things being done by this equipment (e.g. washing, cleaning, garden irrigation, hot accumulating) will be finished when the deficit is gone. This group of equipment/functions dynamically changes during a day, but if we take large a sufficient group of households, there is some average index of those not important functions/equipment, about a half of the equipment items, which could be turned off at any time of a day (see fig. 2 a). The power consumed by this equipment is about 23% of a current households power demand (see fig. 2 b). Another way, if power deficit occurs, by turning off this group of unimportant stuff we are able to return into the power system up to 23% of the household power demand. The data acquired in the research [3] show that, apart from those two presented above groups of household electrical equipment, there is a third group. This group of the equipment represents this stuff which was evidenced by the consumers, but they do not specify the degree of relevance of this stuff’s functions. Their functions are not so critical that the consumers want to pay more for the electricity reliability, but not so unimportant to decide to turn them off if the power deficit occurs. This group of equipment plays some standard, not special, functions to their owners.

By the classification of the consumer equipment’s functions, we imagine that the total consumers’ power demand could be distributed into some parts, and we named them: the “protected” part of the consumed energy which is used by this group of equipment which plays critical functions for the consumers; the “standard” part of consumed energy used by this equipment which plays some standard functions; the “economical” part of consumed energy used by this equipment, which could be turned off any time during a day and finish their tasks another time. The structure of researched households’ electrical equipment’s functionality and the structure of households’ power demand gives some possibilities for energy consumption control (see fig. 2).

This allows for introduction of a new model of electricity consumer powering “the power modes model”[3, 4], where “a part” of consumed energy $E$ is associated with a quality parameter $q$:

$$TR = g(E, q).$$  (2)
The quality parameter $q$ described some individual principles of each power mode $TR$ and the conditions (eq. energy price, hours of access, degree of reliability, etc.) of energy consumption by the stuff powered in the power mode. So, the described households could be powered by three power modes: protected power mode $TR_p$, standard power mode $TR_s$ and economical power mode $TR_e$. The energy consumed by the households in the new model (2) will be the sum of the modes: 

$$E = E_{TR_p} + E_{TR_s} + E_{TR_e}. \quad (3)$$

The model of power modes [4] is similar to another concept of the power consumption distribution – the “UPS model” [22], where the author also proposes to separate some individual power lines in the commercial buildings and to control them individually according to the energy price and energy sufficiency. The power modes model is a more universal model, designed for any type of the electricity consumers.

2.2. The control process
simplifying and paralleling

The model of power modes significantly simplifies the process of energy consumption control. There is no necessity for detailed control of each node of each level of the power system grid (see, fig. 1). At each node there are some simple tasks to be processed, see diagram (fig. 3).

The repeatable tasks of each node of a power system grid hierarchy allows for the control process distribution. There is no necessity for central control of the whole structure of a power system. Each node of the grid could process the control itself and similarly it could manages the energy consumption structure in this part of hierarchy where it is the main node. The idea of distributed control of energy consumption structure in a hierarchy of a power grid system is presented in fig. 4. The total energy consumption (the radius of a circle presents a relative value) is managed by a node on each level of the hierarchy and the structure of power modes’ indexes is aggregated down-up. The possible power demand limitation will be processed up-down and the chosen node will have knowledge “which of the slave nodes ought to turn off their economical power mode to reach the expected demand value”.

By implementation the same functionality of a “smart” node (see fig. 3) it is possible to distribute the decision-making process of the main node to dispersed sub-nodes, which could control some selected subareas. This way the process of energy consumption control will be divided into numerous independent processes of sub-area energy consumption control. The system theory [18] and the theory of control [13] determine the rules of the control art where a complex problem ought to be decomposed into simpler tasks and as Moisiejew said “… there is no known complex system which does not have a hierarchical structure....” [19], so the proposed idea of the energy consumption control process is nothing visionary, but it is important to determinate the main opportunities of the direction of our research.

Fig. 3. The algorithm of electrical energy consumption control, with power modes model using; continuous lines represent internal tasks of a node; marked lines represent tasks realized out of a node (its parent or its children) [9]

The proposed model of hierarchical system of electric energy consumption control [3] is developed to serve this function.

The distribution of process control into dispersed sub-nodes has the following capabilities:

- the sub-processes of control could be executed independently, so the main process could be
parallelized – many dispersed sub-nodes control their sub-areas in the same time;
− the volume of metering data is divided into numerous sub-areas, so a single data repository is smaller than if we centralize the whole control process into one database;
− there is a possibility to implement some virtual sub-areas, which have no geographical equivalents but we decide to do it to improve the control process. It is justified because of natural segmentation of electric energy consumers [17], where such conditions as: their inhabitants, energy consumption volume, individual preferences, etc, specified them as an individual segment, but not closed geographically.

**Figure 4:** The structure of a power system hierarchy with the power modes model implementation [4].

Although the presented idea looks promising, there are a lot of conditions to be fulfilled before the power modes model is put into practice. The paper [7] concentrates on some technical aspects of computer application modelling of the dedicated hierarchical control system. According to one of the authors “The system for measurement and control of electrical energy consumption” for the patent protection [6] the state of art of telemetry technology [11] show that the problem of remote control of distributed objects is resolved. The problem is a large volume of the aquired data [16] and economical aspects of the technical infrastructure.

### 3. SIMULATIONS OF THE POWER MODES MODEL POSSIBILITIES

We concentrate on simulations of possibilities of the power modes model in the implemented Matlab environment. We believe that potential values of proposed method of electric energy control will change the readers’ awareness and bring us a step closer to the solution implementation.

#### 3.1. The object of control description

One of Polish electric energy distributor (with a code name SD2) has divided its administrative area into seven sub-areas, with a symbolic name ZEx (see fig. 5). It distributes energy to many types of consumers [17] but we divide them into two groups: households, which buy the energy in tariff “G” and the other which do not belong to tariff “G”. This division corresponds to the authors’ research [5] which presents the information on the power modes structure of this group of electricity consumers (see fig. 2). To the group of consumers who \( \notin G \) we have linked the standard power mode TRs.

For this structure of the controlled object we have received from the distributor the real data of day-hour power demand for 2007. We have decided that the distributor hypothetical day-hour power supply for this year will be his data of day-hour demand forecast. The received data have been input into the Matlab® simulation environment as 24hours x 365days matrices and subtracted to see the research area (see fig. 6). For the purpose of easier calculation of the hypothetical power “deficit” – the situations where the demand overload the forecasted figures – the distributor has to buy extra energy on the balance market [14], we have decided to narrow the research area to the upper part of the area – the white space in fig. 6 shows the situation where the demand forecast was correct or the forecast exceeded the demand (there is no necessity to buy extra energy).
3.2. The problem and the solution

The problem to be resolved is the power demand decreasing to reduce the dark areas on deficit matrix (see, fig. 6).

We will research how the knowledge about the power modes’ structure of the households’ customers will help us to resolve the problem. We know that up to 23% of the households’ power demand (see, fig. 2) may be reduced by tuning off the devices powered in economical power mode TRe. We try to find out how this volume of energy consumption returned to the power system will help us in the power “deficit” compensation. It is interesting, because the “deficit” is generated by all distributors’ clients, not only by the households. If by the power modes model the energy consumption of households can be controlled and in this way the power demand of the whole distributors’ consumers can be changed – it will be a very good result. And, as it is presented in the next subchapter, this target has been achieved.

The solution, which we have implemented in the simulation environment, is to manage the power modes of each division-nodes of the distributor (see, fig. 5). If the power “deficit” occurs, we turn off the TRe mode of one of the ZEx nodes and if it does not help enough we can take another one.

The decision-making problem which of the ZEx nodes choose for the turning off the TRe mode is another research issue, partly described in [3]. Here we concentrate on the power modes model ability of the power deficit balancing.

We define the indicators of the object state measurement:

- \( TR \) – id’s of ZE nodes where the TR model was implemented;
- \( \sum_{e \in G} \) – numbers of households where the TR model is implemented;
- \( avPr \) – the average power demanded by households powered in the TR model;
- \( E(Pr,T) \) – the total energy consumed by households powered in the TR model in the period of the whole year;
- \( q \) – numbers of situations where the supplied power do not balance the demand of the consumers, in this situation there is a necessity to buy some more energy/power from the generators;
- \( avPn \) – the average power “deficit”;
- \( E(Pn,q) \) – the total energy “deficit”.

The initial object state is presented in fig. 7.

3.3. The results of the object control simulation

As a consequence of a series of simulations of the power modes control of the object hierarchy (see, fig 5) we received the state of the object as presented in fig. 8.

As you can see, the indicator \( E(Pn,q) \) of the whole year energy consumed over the forecast demand decreases from 32,06 GWh in the state before any
control simulation (see, fig. 7), to less than 1 GWh after the restriction of TRe mode simulated on selected division-nodes. The other state indicators also look better.

The selected indicators of the object state between the next steps of the simulation process were printed in the tab. 1.

<table>
<thead>
<tr>
<th>Steps of object control simulations</th>
<th>q</th>
<th>avPn</th>
<th>E(Pn,q)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 None</td>
<td>4603</td>
<td>3.66</td>
<td>32.06</td>
</tr>
<tr>
<td>1 ZE1</td>
<td>1868</td>
<td>1.19</td>
<td>10.44</td>
</tr>
<tr>
<td>2 ZE1, ZE2</td>
<td>1124</td>
<td>0.68</td>
<td>5.95</td>
</tr>
<tr>
<td>3 ZE1, ZE2, ZE3</td>
<td>645</td>
<td>0.38</td>
<td>3.3</td>
</tr>
<tr>
<td>4 ZE1, ZE2, ZE3, ZE4</td>
<td>476</td>
<td>0.27</td>
<td>2.39</td>
</tr>
<tr>
<td>5 ZE1, ZE2, ZE3, ZE4, ZE5</td>
<td>321</td>
<td>0.18</td>
<td>1.59</td>
</tr>
<tr>
<td>6 ZE1, ZE2, ZE3, ZE4, ZE5, ZE6</td>
<td>255</td>
<td>0.14</td>
<td>1.26</td>
</tr>
<tr>
<td>7 ZE1, ZE2, ZE3, ZE4, ZE5, ZE6, ZE7</td>
<td>201</td>
<td>0.11</td>
<td>0.98</td>
</tr>
</tbody>
</table>

The details of the experiment are described in [5].

4. CONCLUSIONS
The results of the simulation of the power modes model implementation in the condition of real distributor presented here show that the model is helpful for the electric energy control. By distribution of the decision-making process of control into dispersed “smart” nodes, the process of control could be parallelized into numerous independent processes. In consequence, that will increase the object control process performance.

There is common interest of the power systems improvement [1, 2, 16, 22] especially in the aspects of the system reliability and electricity sufficiency. The general position is that there is a need for a better power system infrastructure management. The view of “smart grids” or “intelligent grids” becomes more reliable [16], especially in fact of common availability of the teleinformation technology. The remote control of the dispersed objects is not a problem now. The issue is the model of the “actors” participation in the electric energy consumption control process. At present, the platform for the electricity market partner’s cooperation is a price of energy [12, 14], but the customers do not change their power demand if they do not receive the message about price changes online. The message must be clear, universal and easy to apply in the control automation infrastructure. Although, in fact of some technological “backwardness” of a large group of electricity customers, the message ought to be applicable without automation infrastructure, but simply by turning off/on of some customers’ electrical equipment by the customers themselves, after e.g. radio or TV messages. The proposed power modes model is accurate to resolve this issue.

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Słowa kluczowe: model trybów zasilania, sieci inteligentne, sterowanie rozproszone, hierarchiczne systemy sterowania, inteligentny pomiar i sterowanie


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