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Demand-Side Management Efficiency Estimation in Microgrids Performed by Smart Metering Systems

Vladislav O. Samoilenko, Andrew V. Pazderin

Department of Automated Electrical Systems
Ural Federal University named after the first President of Russia B.N. Yeltsin
Mira 19 str., 620002 Yekaterinburg (Russia)
Phone/Fax number:+007 343 3591615, e-mail: **vvsamoylenko@yandex.ru**, **pav@daes.ustu.ru**

Abstract. The ongoing implementation of the energy accounting tariffs with differentiated rates, which depend upon the market conditions and may change in a short-term perspective, provide the possibility to use it as a financial incentive base of the Demand-Side Management (DSM). On the other hand, modern hi-technology energy metering and accounting systems with a large number of functions and consumer feedback are the good means of DSM. Existing systems of Smart Metering (SM) and consumer feedback are usually not fully used. So, the efforts to combine the market principle, Smart Metering and a consumer feedback are essential.

The paper presents multi-purpose system of mathematical statistics and algorithms of DSM efficiency estimation useful for both the consumers and the energy companies. The estimation is performed by SM Data processing systems. The system is focused primarily on a retail market support in Microgrids due to clear and simple framework without the necessity of making large-scale calculations. It contributes to the energy efficiency and a distribution process improvement by the motivation (manual management) or by the Smart Appliances interaction (automated management).

Key words

Demand-side management, Smart Metering, Microgrids, Economics, Energy efficiency.

1. Introduction

The development of market mechanisms and electricity markets of the global energy sector leads to changes in concept of microgrids control and management [1]. Nowadays many works regarding the demand-side management in microgrids are devoted to control, maintenance, operation and power quality issues [2],[3]. Primarily, they are focused on particular component models consideration and corresponding electrical parameters. Also, the issue of Smart Concepts interaction is considered from this point of view [4]. Nevertheless, it seems to be promising to establish more generalized approach based on energy balances and combined electrical and economical parameters to be beneficial to different market participants.

Advanced metering of electricity and power by accounting tariffs with multiple rates differentiated by times of the day becomes more complicated. There is the perspective for rate changes for medium and small intervals of time. Energy companies of the UK and some other countries have an experience of rate change for the medium period of time [5]. A number of government regulations support the course.

On the other hand, increased development density and grids connectivity as well as increased energy consumption of large cities leads to changing the requirements for electricity metering systems. The Smart Metering concept provides for a broad implementation of modern informational and measuring components [6].

Taking this into account, the common interests of consumers and energy companies are growing. There is a need for a program of market participants' information support and evaluation of electrical parameters, focused on differentiated by time intervals accounting, which is designed to incentive the participants and provide a non-contractual management of power consumption, distributed generation and load of the grid components. The penetration of these informational resources is beneficial to all the market participants [7]:

1) *Consumers* have an opportunity to assess their power consumption and manage it automatically depending upon the rates as well as to reduce

their energy costs, to choose their power supplier with the most favorable terms.

2) *Owners of distributed generation* can get the maximum profit from its use.
3) *Energy companies* are able to influence a demand, a proposal for the distributed generation, reducing or changing the load of the grid components. Also they have an opportunity to conduct advanced statistics of consumption as well as automation of financial and contractual processes.

Existing systems of Smart Metering billing usually provide little general information about consumption curve, bills and compared data, but not the advanced statistics about the correspondence of financial and electric parameters. Also, consumer feedback is usually not fully used.

So, the efforts to combine the market principle, Smart Metering and a consumer feedback are essential. Compared to the other existing approaches, the presented approach is rather simple and clear. It is based on energy balance values and aimed primarily at developing the incentives their selves and the feedback to a customer, not the models of microgrids and parameters fluctuation.

2. The Dual-Purpose Incentives

Besides of the consumers' efforts to contribute the global idea of energy efficiency and ecology improvement, the main incentive for the consumers is an opportunity to decrease their energy costs.

An analysis of the potentials to decrease the costs is aimed at the determination of rates schedule and a consumer's load curve correspondence extent. Also the analysis includes the influence of technical losses.

A case when there are M different rates (or prices of a complex rate) offered to consumer is considered. All the rates (or prices) can be ranged using their values by the principle "cheap – expensive". The most expensive rate j may be assigned to the effectiveness of α_{max} = 0%, the cheapest - α_{min} = 100%. Rates with an intermediate price p_j can be assigned to an intermediate value of α_j, proportional to the relative price difference between this value and the minimum price to the price difference of these two extreme rates.

The principle of ranking is shown in Figure 1.

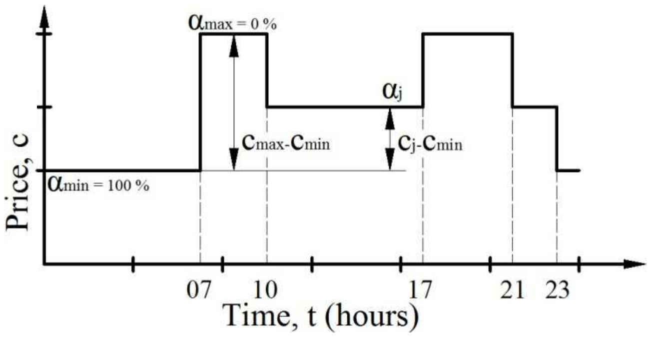


Fig. 1. The rate efficiency.

There are three rates: night (from 23:00 to 07:00), semi-peak (from 10:00 to 17:00 and from 21:00 to 23:00) and peak (from 07:00 to 10:00 and from 17:00 to 21:00). The basic parameter of rate *j* efficiency *a* can be defined as normalized relative value obtained by minimum c_{min} and maximal c_{max} prices of night and peak rates, correspondingly:

$$a_j = \frac{1-(c_j - c_{\min})}{(c_{\max} - c_{\min})} \cdot 100\% = \frac{(c_{\max} - c_j)}{(c_{\max} - c_{\min})}, \quad j = 1...M \quad (1)$$

Weight-average rate use efficiency index *e* is one of the most important parameters. It is based measured energy values W_j (or relative energy values W_{rj}) obtained by SM:

$$e = \sum_{j=1}^{M} a_j \cdot W_{rj} = \left(\sum_{j=1}^{M} a_j \cdot W_j \right) \Bigg/ \left(\sum_{j=1}^{M} W_j \right), \quad (2)$$

Thus, the coefficient of efficiency *e* is the weighted average of the rates. Its value represents the opportunity of savings for the consumer. There are two extreme cases:

1) *All the electricity* was consumed during rate period with α_{max} = 0%, which means the consumer didn't use the opportunity of savings.
2) *All the electricity* was consumed during rate period with α_{min} = 100%, which means the user used all rate for savings.

The actual value of the coefficient of efficiency rates is between 0% and 100%.
The weight-average rate use efficiency index *e* has a triple meaning:

1) *Utilized economy* fact percentage.
2) *Rates schedule* and a consumer's load curve correspondence extent.
3) *The elasticity of a demand*.

The consumer is able to estimate his savings and choose the most appropriate to him rate. The estimations are suitable for a-priori and a-posteriori dynamic rate selection.

The energy company is able to estimate demand-side management efficiency due to the fact that rate use efficiency index is approximately equal to the elasticity of a demand.

Using the rate use efficiency index *e*, it is possible to determine the economy *E* and lost savings E_l:

$$E = \frac{e}{100} \cdot W \cdot (c_{\max} - c_{\min}) \quad (3)$$

$$E_l = \left(1 - \frac{e}{100}\right) \cdot W \cdot (c_{\max} - c_{\min}) \quad (4)$$

Another important parameter is the smoothing of load curve. It contributes to equipment lifetime and durability increase as well as peak lines load decrease, so it is very important. From the point of view of Math Statistics the load change can be characterized by standard variation coefficient *v*. But this parameter is not demonstrative even for engineers.

One of the ideas how to estimate the variation using this parameter like an incentive for a consumer is to show him the economy based on the losses decrease. The losses in cables and wires connecting a consumer to electricity mains are considered.

From the theory of electrical power engineering it is well known that the minimum of losses during a period of time corresponds to the case when the load flows are equal at all the parts of the period.

It is useful to estimate relative reduction of the loss for single rate and the relative reduction of losses during of time period of *n* intervals, correspondingly:

$$r_t = \left(1 - \frac{1}{1+v^2}\right) \cdot 100\% = \frac{v^2}{1+v^2} \cdot 100\%, \quad (5)$$

$$r = \frac{c\Delta W_{av}}{c\Delta W} = \frac{\sum_{j=1}^{N} W_{avj}^2 \cdot n_j \cdot v_j^2}{\sum_{j=1}^{N} W_{avj}^2 \cdot n_j \cdot \left(1+v_j^2\right)} \cdot 100\%. \quad (6)$$

where v - coefficient of consumption variation; ΔW_{av} – losses for the case of absolutely uniform consumption; ΔW_{av} - losses for the case of an arbitrary consumption.

Studies and the calculations show that during the day typical v vary from 0,23 to 0,75 for different rate periods and losses decrease is from 7 % to 30 %, correspondingly. Taking into account that typical losses level is about 10 % for buildings' wiring, savings will be from 0,7 % to 3 %.

Sometimes the problem at hand is not the value of maximum power consumption itself, but the dynamics of load increase at peak times. The concept of easy load curve smoothing by means of Smart Appliances control centre and Feedback centre interaction is considered (Figure 2).

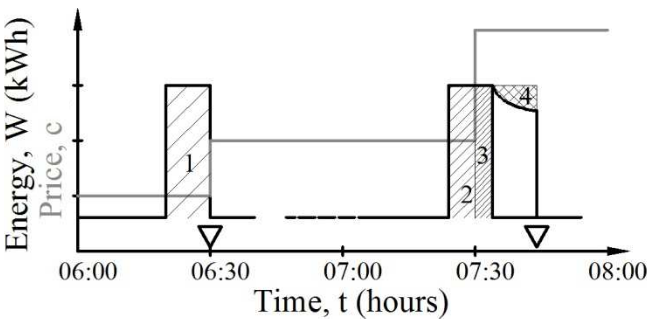


Fig. 2. The planning principle.

The system should automatically account the warm-up durability which is required for the equipment, and to compare it with the time rate change time. In everyday life for consumers this turns out to be convenient - the opportunity to receive the result of the electrical installations at the time of morning rise or production process run. In the first case (Figure 2) readiness time is equal to the time rate of change. From the point of view of energy company as well as the consumer it is efficient to switch on the device so that the power consumption accounted by cheaper rate (area 1). Operation is planned in such a way that the time of a rate of change is also a readiness time of a process. When the readiness time comes later than time of rate change (the second case), it is profitable that electrical energy is accounted partially by cheaper rate (area 2) and partially by more expensive rate (area 3). The condition of profitable operation:

$$C_4 \le C_3 - C_2 \quad (7)$$

where C_4 are the costs of equipment downtime (e.g., losses), C_3-C_2 is a profit gained by the rate difference.

3. Private Distributed Generation Estimation

The particular installations of dispersed generation are under consideration. Such installations are often privately owned and have small power.

First of all, the two effects of the introduction of consumers' generation cause increased attention of energy companies:

1) *The effect of masking the load* when the sudden shutdown of consumers' own generation may results in feeders overload due to the fact that they was not designed for full capacity.
2) *The effect of the consumers' generation far exceeding the demand* (e.g. during the night) can cause increased losses and undesirable reverse flows of a great value.

The RMS-imbalance of generation to the load shows the extent of balancing during M periods of time:

$$b = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{W_i - W_{gi}}{W_{gi}}\right)^2} \cdot 100\%, \quad (8)$$

where W_i is load during a single period of time, W_{gi} is generation during a single period of time.

For the case when the imbalance value is far from zero, a permanent connection to the main grid being a damping component is necessary for the potential island of load and generation.

One-time maximum deviation of the generation from load:

$$D = \max\left(\frac{W_{gi} - W_i}{W_i}\right) \cdot 100\%, \quad (9)$$

This parameter shows the extent of instantaneous damping necessity during some particular periods of time and characterize feeders maximum load.

It is known that from the point of view of distribution utilities the benefits from the presence of dispersed generation is primarily consist of load coverage and feeders flows reduction. It results at the possibility of postponing capital investments in grid reinforcement. Maximum feeders load corresponds to the period of load curve maximum, especially at the post-failure conditions or at the repair schemes. Demand for dispersed generation and own generation of consumers in these conditions increases. That's why the dual-purpose incentives include operation time during the period of the peak rate, the share of electrical energy produced during the period of the peak rate and the income from the generation of electricity.

$$t_{\max} = \left(\frac{T_{\max} - T_{st}}{T_{\max}}\right) \cdot 100\%, \quad (10)$$

where T_{max} is a duration of the peak rate (special or post-failure rate), T_{st} is a downtime of dispersed generation installation during the period of the peak rate.

The share of electrical energy produced during the period of the peak rate:

$$d_{\max} = \sum_{i=1}^{n_{\max}} W_{gi} \Big/ \left(P_g \cdot n_{\max}\right) \cdot 100\%, \quad (11)$$

where n_{max} is a number of single time periods during the peak rate, P_g is a generation power.

Using the high-price rate c_{max} it is possible to calculate the revenue R as a product of c_{max} and W_{gi} as well as lost revenue due to equipment downtime:

$$R_l = \left(1 - \frac{d_{\max}}{100}\right) \cdot c_{\max} \sum_{i=1}^{n_{\max}} W_{gi}, \quad (12)$$

The mentioned functions and components of statistics are also available using the Individual Statement.

4. Estimations Performed by Smart Metering

The DSM estimation includes the multi-purpose system of mathematical statistics and algorithms of DSM efficiency estimation useful for the consumers, distributed generation and the energy companies. The estimation is performed by SM Data processing systems. The structure of interaction is shown in Figure 3.

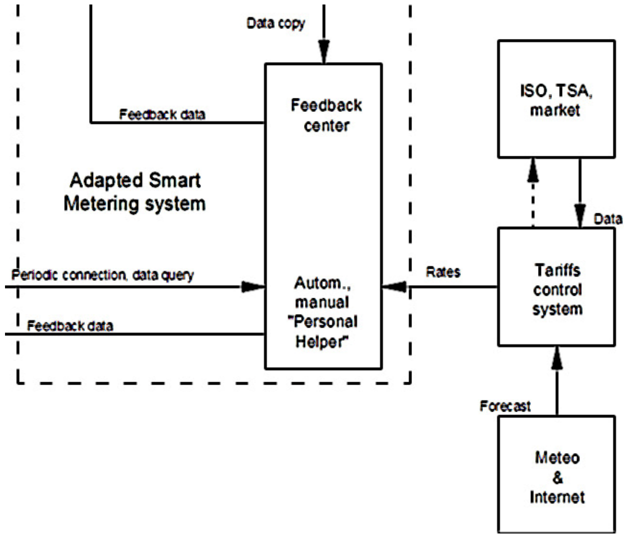


Fig. 3. The structure of interaction.

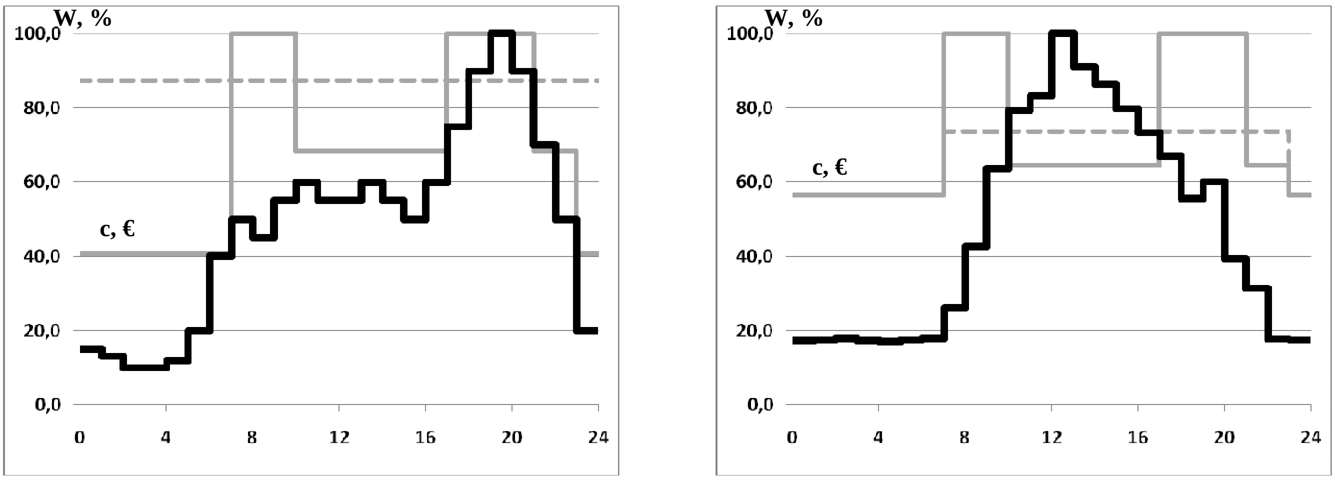
The cores of automated remote metering and advanced metering infrastructure are not shown in the Figure 3.
The system is focused primarily on a retail market support. It contributes to the energy efficiency and a distribution process improvement by the motivation (manual management) or by the Smart Appliances interaction (automated management). The feedback of SM can be integrated with Smart House and Smart Energy. In a manual mode feedback data are outputted to Individual Statement in easy-understandable form, in automatic mode data are used by Smart Appliance control center through WLAN/HAN.

The system includes the unit of dynamic rate change depending upon outer parameters.

5. Case Study

The system proposed is planned to be applied for the accounting system of Ural Federal University study building No. 8 and its campus and to contribute to The University energy efficiency improvement.

So, the calculation for the perspective efficiency was made. The load curve of a domestic building belonging to the University campus and study building No. 8 is shown in Figure 4, *a* and 4, *b*, correspondingly.



a) *b)*

Fig. 4. The load curves

Table I. – Domestic building DSM efficiency estimation

Rate	Time period	Month consumpt., kW*h	Rate value, €/kW*h	RE α, %	RUC ε, %	Cost (α=49,9), €	Economy lost, €	Relative economy, %
Three periods	Peak	36,2	6,80	0,0	35,7	1608,1 (1435,5)	776,49 (603,9)	9,9 (19,4)
	Semi-peak	130,6	4,65	53,3				
	Night	133,2	2,77	100,0				
One period	Day	300,0	5,94	21,3	21,3	1782,0	950,4	0

Table II. – Study building No. 8 DSM efficiency estimation

Rate	Time period	Month consumpt., kW*h	Rate value, €/kW*h	RE α, %	RUC ε, %	Cost, €	Economy lost, €	Relative economy, %
Three periods	Peak	6778	25,31	0,0	37,6	411114	100337	0
	Semi-peak	12281	16,40	81,0				
	Night	2668	14,29	100,0				
Two periods	Day	19059	18,68	60,3	65,2	394149	83371	4,1
	Night	2668	14,29	100,0				

The data for these two buildings are presented in Table I and Table II, correspondingly.

The extent of load curve (black colour) to rate curve (grey colour) correspondence can be well seen in Figure 4. The one period price for household building is shown as dashed grey line as well as day price for study building No. 8, if a case of two periods rate is considered.

As it can be seen, the DSM efficiency system estimates that the real efficiency for household building was about 21% due to one period rate, but dynamic changing the rate and making the consumption efficiency close to 49,9 % by means of Smart Appliances use gives sufficient economy of 19,4 % (9,9 by means of dynamic rate selection only).

Vice versa, a simple rate was chosen for the study building No. 8 due to it's specific load curve. Taking into account the relation between the prices of the three period rate and two period rate, it is more profitable to select the last one. It gives economy of 4,1%.

6. Conclusion

A new generalized approach to the DSM efficiency estimation is proposed. Compared to the other existing approaches, it is clear and rather simple. It is based on energy balance values and aimed primarily at developing the incentives their selves and the feedback to a customer, not the models of microgrids and parameters fluctuation. The entire system of the mathematical statistics including the dual-purpose incentives was established (Table III).

Table III. – Important Parameters

Parameter	Sign	Utilization	
		Energy Compani es	Demand Side
Rate efficiency	a [%]	Price signal	Incentives
Rates utilization coefficient	e [%]	Demand flexibility	Economy potential

Parameter	Sign	Utilization	
		Energy Companies	Demand Side
Economy	E [€]	-	Utilized
Loss of economy	E_l [€]	-	Missed
Average consumption	W_{av} [kW*h]	Balances, statistics	General
Consumption variation coefficient	ν [r.u.]	Statistics	-
Relative losses reduction due to load curve leveling	r [%]	Balances, statistics	Economy potential
Percentage of the load covered by distributed generation	cv [%]	Balances, statistics	Utilized
Generation-to-load average unbalance	b [%]	Line av. load	Missed
One-time relative generation-to-load unbalance	D [%]	Line max. load	-
Absence of idles during the high-price rate	t_{max} [%]	Offer flexibility	General
Percentage of generated electrical energy value in comparison with the max. value	d_{max} [%]	Offer flexibility	General
Profit gained by distributed gener. during the high-price rate	R [€]	-	Utilized
Loss of profit	R_l [€]	-	Missed

The system of DSM efficiency estimation provides a number of benefits to different parties of electricity market.

1) *Consumers* are motivated by financial incentives and informed by advanced analysis information about rates, economy, and schedule.
2) *Energy companies* are informed about the consumers' response, load parameters and they have an opportunity to smooth load curve by means of appropriate rate signals.
3) *The social aspect* includes sufficient energy efficiency improvement.
4) *Distributed generation* has an opportunity to gain the maximum profit.
5) *Clear and simple* framework is useful for Microgrids with the huge number of elements complicating large-scale calculations.

All the information contained in the evaluation is both engineering and motivational (incentive) character. On the one hand, formal recommendations to the consumer are necessary as clarification of opportunities to improve the quality of consumption; on the other hand, a simple formal approach is not comprehensive. The issuance of such recommendations should be implemented with care and some of the issues of engineering psychology should be used.

Strictly speaking, the recommendations should be linked to the technical, economic, operational and marketing issues facing the energy company at the moment of the recommendations issuance.

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