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ASSESSMENT OF CONSUMERS POWER CONSUMPTION OPTIMIZATION BASED ON DEMAND SIDE MANAGEMENT

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Abstract

To ensure the functioning of the energy system, coordination and increase the efficiency of its parts need new control mechanisms. Generation, transmission and consumption of electricity needed control mechanisms that include integration of self-organizing power and heat supply systems, built on multi-agent principle. Also they must correspond intellectual basis, monitoring and accumulation. This includes effectiveness assessment of the state and analysis of technical, technological and organizational management mechanisms. One of the main parts is interaction principles of energy systems in accordance with European Community policy at various levels at liberalized electricity market.

In most developed countries, demand management programs are widely used as a means of harmonizing the modes of generation and consumption in the power supply system. The main direct methods are set in the form of electricity tariffs. Indirect methods are set in the form of programs to manage electricity demand and the possibility of their application to manage electricity demand. Methods for estimating the unevenness of the daily schedule of electricity consumption and the factors influencing the technological environment are presented.

The work aims at scientific and applied problem – finding methods of estimation and features of managing the demand for electricity.

The use of the proposed estimation methods of electricity consumption influence non-uniformity on the level of power supplies system losses based on Frize Q_F power and optimization of consumers' operation modes in the power supply system is considered.

Approaches and optimization mechanisms of the daily electricity consumption on the example of a residential complex with the possibility of energy accumulation are offered.

Keywords: DSM, energy efficiency, smart grid, power supply optimization, consumption schedule.

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1. Introduction

The development of modern power systems based on Smart Grid (SG) technologies allows consumers to participate in Demand Side Management (DSM) programs. DSM can solve a number of problems related to covering the unevenness of daily profiles of energy generation and consumption directly on the consumer side, and within the framework of a Virtual Power Plants (VPP) and the global trend of increasing electricity demand.

DSM is about using consumers demand elasticity to keep energy balance or provide additional services [1]. It has become more popular with the new opportunities achieved from SG technologies development [2] Such technologies like 'Internet of Things'(IoT) [3] can provide a smart peak electricity in real-time mode. Uncertain factors like load prediction can be solved with the help of communication technologies of SG [4]. In such case, price and reward based DSM mechanism can be used for maximization of users profit. Modifying users load billing scheme to shift their load from peak hour to the off-peak hours [5, 6]. Using price-based as well as reward-based DSM schemes [7], instantaneous load billing schemes [8, 9], admission control, load balancing, and demand response management in Smart Buildings and Zero Energy Building [10–12]. Implementation of using different energy price models which optimize the difference between the value and cost of energy and «elasticity» and «time of use» pricing concepts and use of energy storage [13] technologies which optimize the interaction between suppliers and consumers [14–16]. The user and the distributor communicate with each other to find the optimal conditions for energy balancing, and provide additional ecological benefits, provide significant economic, reliability and environmental benefits without additional network and generation infrastructure cost [17, 18].

DSM and Demand Response (DR) are main applications of SG. DSM refers to energy consumption influence at demand side while DR refers to the change of user's electric consumption such as customer-oriented DSM [19, 20] in response to external incentives or performances which in its terms provides a powerful stimulus to energy efficiency [21]. Both topics are different sides of same coin and were very popular in scientific papers in last years but problems still remain open in fields of dynamic pricing and technical implementation (availability, access-control and technical reliability of proposed solutions) [20, 22]. SG and DSM technologies leads to the introduction of power supply systems with DG sources and Prosumers. An example of power supply systems with DG sources and Prosumers can be both a VPP and a section of the power system with a significant number of Prosumers or renewables.

DSM or DR aims to change the demand of energy consumers through the use of various methods, such as financial incentives or energy efficiency initiatives [22, 23]. In power supply systems with DG sources, DR refers mainly to a temporary reduction in electricity consumption, the average duration of measures is 1–4 hours and is a response to price signals from the electricity market or the electricity network operator. The effect of the application is measured in kWh of consumed electricity (also refers to kW of peak consumption reduction) and cost reduction.

In contrast to DR, measures related to DSM are aimed at long-term operation and include reducing the overall level of energy consumption through the implementation of measures to improve energy efficiency and energy saving. The effect of the application is measured in kWh (also refers to kW reduction of peak consumption).

Smart Power Supply Systems are complex systems. Their complex structure and variety of generation sources (Distributed Generation (DG) sources including renewables), and the presence of a large number of power electronics devices that provide steady-state modes of their operations makes it absolutely impossible to provide optimum working conditions for each consumer in such systems in advance. One of the best existing mechanisms of energy processes optimization nowadays is DSM mechanisms.

DSM strategies and mechanisms have been used in the power industry for many years, paper [24] describes the goal of DSM to provide efficient usage of the power system assets and reduce electricity costs for customers. In fact, paper [25] results shows DSM alters the load profiles of customers through a variety of programs, such as peak clipping, load shifting, valley filling, energy conservation. Therefore, authors [26] recommend electric utilities to incorporate DSM in their resource planning by performing cost/benefit analysis. Paper [27] results shows promising infrastructure of the Smart Power Supply Systems with Prosumers featuring real-time communication and data flow among electric utilities and customers will support DSMs by providing more efficient load controllability and incentives based on dynamic electricity rates, in the nearest future.

A number of recent research studies have considered the impact of incorporating Distributed Energy Resources (DER), such as electric vehicles [28] and DG-storage systems [29], on DSM and system reliability. The effects of DSM on the adequacy of power supply have been previously studied in [30]. The researchers in [26] indicated that the highest reliability benefit of DSM in terms of outage cost reduction is associated with the large user sectors rather than small residential and agricultural loads. Keeping this in mind the assessment mechanisms for represented systems must take into account peculiarities of operation of all system's elements which in its turn will allow to use DSM mechanisms in the most effective manner.

All this suggests that it is advisable to conduct a study on peculiarities of the structure and operation of the power supply systems with DG sources and Prosumers which are highly affected by DSM mechanisms.

The aim of the study is demand side management components and demand response mechanisms for daily consumption optimization.

To achieve this aim, the following objectives are accomplished:

– analyze the optimality of processes in power supply systems with DG sources and Prosumers;

– define optimization criteria for power supply systems with DG sources and Prosumers;

– define non-sinusoidal impact on the Fryze reactive power Q_F change;

– optimize electricity consumption profile for household in case of DSM programs implementation.

2. Materials and methods

The research is based at theoretical methods of uneven consumption influence at power system assessment. As an additional indicator for optimization assessment proposed Fryze reactive power Q_F as indicator of optimal schedule deviation. Optimization of household's basic equipment daily consumption schedule with assumption of willingness participation as flexibility coefficient of demand k_g was done in MatLab as the goal attainment problem for minimizing a multiobjective optimization problem.

3. Results

3. 1. Mode optimization features in DG power supply systems with DSM integration

DSM has traditionally been seen as a means of reducing peak demand for electricity in the grid [31]. By reducing the total load on the electrical network, DSM allows to reduce the number of accidents by reducing the number of outages, as well as increase the reliability of the system [32]. The use of DSM programs makes it possible to overcome barriers that prevent the adoption of many related energy efficiency programs and to raise funds for the economic benefits of rational use of electricity and savings from off-peak consumption.

The main mechanism of DSM programs [33] among others, it includes direct control and tools to change peak and off-peak consumption together with energy efficiency programs. Despite global trends, the issue of managing electricity demand in Ukraine remains open [34].

In the general case, the objective function for the organization of the process of solving the mathematical expression of the goal of optimal control of the system is formalized in the form of a function of control quality [33]. For a particular case, the objective function of the optimization problem can be written as:

$$F_{gen} = (\Delta U_{gen} \Delta I_{gen} \Delta f_{gen} \Delta\varphi_{gen} \Delta P_{gen} g_{gen}),$$

$$F_{\substack{transfer\\transformation}} = (\Delta U_{transfer}, \Delta I_{transfer}, \Delta f_{transfer}, \Delta\varphi_{transfer}, \Delta P_{transfer}, g_{transfer}),$$

$$F_{cons} = (\Delta U_{cons}, \Delta I_{cons}, \Delta f_{cons}, \Delta\varphi_{cons}, \Delta P_{cons}, g_{cons}),$$

where ΔU – voltage deviation; ΔI – current deviation; Δf – frequency deviation; $\Delta\varphi$ – power factor changes; ΔP – power loss; g – other factors, which arise as a result of uneven processes, and which must be considered when optimizing the modes of operation in power supply systems with DG sources and Prosumers.

The general objective function is vector, in some cases in case of its consideration scalarization is necessary, i. e., knowing initial conditions and restrictions, to define such mode of work which maximizes or minimizes the uniform set criterion indicator.

Consideration and analysis of the operation of the system should be on the time interval T_T and distinguish 4 groups of modes of the equation between the graphs of the instantaneous values of the generation power $p_g(t)$ and consumption $p_c(t)$:

1) $p_g(t)=p_c(t),\ \forall t,\ t\in[0,T_T];\ P_g=P_c$;

full coordination of generation and load (consumers) operation modes;

2) $p_g(t)\neq p_c(t);\ \frac{1}{T}\int_0^T p_g(t)\mathrm{d}t=\frac{1}{T}\int_0^T p_c(t)\mathrm{d}t;\ P_g=P_c$;

should be provided by the use of technical means, first of all systems of energy storage, reactive power compensation, compensation of non-sinusoidality and asymmetry;

3) $p_g(t)\neq p_c(t);\ P_g<P_c$;

should be implemented not only through technical means, in particular, given for the second group of modes, but also primarily through the implementation of DSM programs;

4) $p_g(t)\neq p_c(t);\ P_g>P_c$;

should provide not only to increase the levels of electricity consumption of the existing load, but also the ability to connect additional loads.

3. 2. Demand Side Management optimization features in power supply systems with DG sources and Prosumers

In the case of extending the concept of Fryze reactive power Q_F to an arbitrary time interval $\tau=T_T$, the power $Q_{F\tau}$ can be used for retrospective, prospective and real-time analysis. This approach must identify the effects of suboptimal components: voltage deviation ΔU, current deviation ΔI, presence of voltage and current harmonic components $k_{\Pi u}$, and $k_{\Pi i}$, reactive component ($\cos\varphi\neq 1$) [35].

Having identified the indicator of suboptimality, which characterizes the efficiency of regulation and determines the level of suboptimality of energy transfer, let's analyze the available load profiles, in which there are three main options:

1) retrospective with decreasing time interval δ;
2) perspective within the analysis of processes with increasing time interval δ;
3) real-time analysis at $\delta=0$.

The application of Q_F to assess the non-uniformity of processes will be shown on the example of a mode characterized by the voltage and current values U_i and I_i, $i=1,...,n$, T_i – the duration of the i-th interval, and $P=U_0I_0$, where U_0, I_0 – the average values of voltage and current. If $\cos\varphi=1$ for the interval $T_m>T_g$, where T_g – the period of the grid, one can write an expression for the power of the Fryze Q_F in the form:

$$Q_F=\sqrt{\left(\sum_{i=1}^{n}U_i^2\frac{T_i}{T}\right)\left(\sum_{j=1}^{n}I_j^2\frac{T_i}{T}\right)-U_0^2I_0^2},\tag{1}$$

which with $\delta_i=T_i/T;\ \sum_{i=1}^{n}\delta_i=1$ can be written as:

$$Q_F=\sqrt{\sum_{i=1}^{n}U_i^2\delta_i\cdot\sum_{i=1}^{n}I_i^2\delta_i-\sum_{i=1}^{n}(U_i\,I_i\,\delta_i)^2}.\tag{2}$$

Using the indicator $k_{\Delta opt}=Q_F/P$.

Let's analyze some components of the influence of suboptimal factors on the amount of losses:

1. The effect of voltage deviation ΔU, with $\Delta I=0$, $I_1=I_2$; $U_2=U_1+\Delta U$, let's obtain:

$$Q_F=I_1\Delta U\sqrt{\delta_2-\delta_2^2},$$

2. The effect of current deviation ΔI, with $\Delta U=0$, $U_1=U_2$, $I_2=I_1+\Delta I$, let's obtain:

$$Q_F=U_1\Delta I\sqrt{\delta_2-\delta_2^2},$$

3. The effect of the time interval increasing ($\delta_2 = \delta_2 + \delta_2^*$), let's obtain:

$$Q_F = {}_1\sqrt{\Delta U^2\left(\delta_2 + \delta_2^*\right) - 2U_1^2\delta_2^* - \left(U_1\delta_2^* + \Delta U\left(\delta_2 + \delta_2^*\right)\right)^2}.$$

In the case of entering relative values for two time intervals δ_1, δ_2, the value $k_{\Delta opt} = Q_F/P$ will be as follows:

$$\begin{aligned} k_{\Delta opt} &= (1+\Delta U)^2(1+k_{pu}^2)\cdot(1+k_{pi}^2)(1+\Delta I)^2\delta_2^2\sin^2\varphi_2 + \\ &+ 2\delta_1\delta_2(1+k_{pu}^2)(1+k_{pi}^2)(1+\Delta U)(1+\Delta I)(1-\cos\varphi_1\cos\varphi_2). \end{aligned} \quad (3)$$

The optimization of certain types of equipment is based on the consideration of the function:

$$Q_F = F_Q\left(U, I, \cos\varphi, \Delta U, \Delta I, k_{pu}, k_{pi}\right), \quad (4)$$

and involves the use of the criterion $k\Delta_{opt} = Q_F/P \to \min$ simultaneously with the implementation of the DSM program. Optimization of equipment operation involves the following steps:

1) determine the factors of influence and the formation of the equation (3);

2) changes in the value of Q_F from changes in the absolute values of indicators of influencing factors, such as changes in function, are estimated $Q_F = F_Q\left(U, I, \Delta I\right)$;

3) the number of zones $n_{\Delta I}$ of changes in the value of Q_F is estimated and changes in the value $Q_{F,j}$ in case of change of ΔI_j; $j = 1, ..., n_{\Delta I}$ are calculated;

4) for the j-th zone for certain types of equipment control influences are defined on the basis of the base of sets of functional dependences of control of a mode of operation of each type of equipment formed according to application of DSM programs which provide $k_{\Delta opt} = Q_F/P \to \min$.

3. 3. Methods of power supply system stability assessment

All the elements of aforementioned systems are connected by the continuous processes of generation, transformation, transmission, distribution and storage of electricity. In this stream terms such as «process stability» and «process capability» which are very common can help handling this problem.

A process is said to be stable when all of the response parameters that let's use to measure the process have both constant means and constant variances over time, and also have a constant distribution.

Process capability analysis entails comparing the performance of a process against its specifications. It is possible to say that a process is capable if virtually all of the possible variable values fall within the specification limits.

Using these definitions for power supply systems with DG sources and Prosumers it is possible carefully indicate the variables (indicators of operation) for the assessment.

One of such Process Stability Indicators (PSI) may be the capability of different converters and compensation devices, which are commonly used in the grids with different types of renewables, to influence the grid parameters (e. g. power quality, reliability etc.).

Another indicator may be shown as the sensitivity of the mode parameters to the deviation of the electricity parameters as a converter output signal:

$$S_q^{\varphi} = \frac{\varphi(q+\delta) - \varphi(q)}{\delta},$$

where S_q^{φ} – characterizes the sensitivity of the function φ to change of the parameter q. The control function or energy characteristic can act as a function φ, and the quantity q can characterize both the magnitude of the distortion of the energy characteristic and the output electrical parameter.

In order to ensure the optimal functioning of the power supply systems with DG sources and Prosumers it is important to compare the different conditions of power supply in terms of technical quality, considering their economic importance (cost). This value makes possible to compare technical solutions even if they have different levels of power quality.

The concept of quality of power supply should be considered for the assessment as a set of properties of the power supply system, which determine the degree of suitability of providing consumers with the specified power quality at the required level of reliability.

3. 4. Methods of reliability evaluation and approach

Nowadays reliability and power quality are the major parts of power supply quality according to EN 50160 standard. Reliability is assessed by the indicators proposed in IEEE 1366 standard in the US and by the indexes SAIDI, SAIFI, MAIFI, ENS which are presented in this standard in Ukraine. Returning to the assessment in power supply systems with DG sources and Prosumers One must consider the problems which different DG sources present to the grid due to the variable behavior of the primary energy source (e. g. solar insulation, wind capacity etc.) and the complexity of the power supply systems with DG sources and Prosumers modes of operation. Due to stochastic behavior of the renewable sources and loads, conventional reliability assessment techniques can't be used in power supply systems with DG sources and Prosumers applications.

For the complex assessment of the power supply systems with DG sources and Prosumers reliability one can use the Normalized Reliability Index – NRI, which should be based on the targeted values of the reliability indexes.

While increasing the reliability in the power supply systems with DG sources and Prosumers one should target to decrease these indexes below the level of the appointed values.

Taking this into account the complexity of the structure and modes of power supply systems with DG sources and Prosumers, described earlier, the reliability index should be normalized for any configuration of DG sources (wind, solar etc.) and diverse modes of power generation.

Depending on the mode of power supply systems with DG sources and Prosumers for the reliability assessment it's proposed to divide all power sources into 3 types:

1. Sources of centralized power generation.
2. Uninterruptible distributed generation sources.
3. Distributed generation sources with variable output parameters dependent on weather conditions and not regulated by human.

Outages should also be divided into ones caused by weather conditions/absence of primary energy source and ordinary outages.

3. 5. Analysis of the non-sinusoidal impact on the change in the Q_{F} magnitude

The influence of harmonic components on the values $i(t)$ and $u(t)$ is calculated as:

$$Q_F^2=\frac{\sum_{j=1}^{n}U_{M,j}^2\left(1+k_{nu,j}^2\right)\sum_{j=1}^{n}I_{M,j}^2\left(1+k_{ni,j}^2\right)-U_{M,j}^2I_{M,j}^2\left(\left|\varphi_j^u-\varphi_j^i\right|\right)}{2}.$$

When considering electricity processes during the day, the ratio should be approximated by four components **Fig. 1** that reflect the average levels of voltage and current. This approach formally reflects electricity consumption in the evening and morning highs and night and day lows [33].

Considering such a case for the day, an expression for the Fryze reactive power, in the case of four time intervals and the theoretical assumption of fully active consumption, knowing the magnitude of the optimum level of voltage and currents for the intervals, it is possible to write the values for voltages and currents as deviations from the optimal level by magnitude ΔI and ΔU [33].

$$U_{norm}=\frac{U_1\Delta t_1+U_2\Delta t_2+U_3\Delta t_3+U_4\Delta t_4}{T},\ I_{norm}=\frac{I_1\Delta t_1+I_2\Delta t_2+I_3\Delta t_3+I_4\Delta t_4}{T}.$$

The closest to the real conditions is the mode of operation of the conditional installation (generator – load). A daily interval of 24 hours was considered [32, 35]:

$$Q_{F,24}^2=(U_{norm}^2+\sum_{j=1}^{4}\Delta U_j^2\delta_j)(I_{norm}^2+\sum_{j=1}^{4}\Delta I_j^2\delta_j)-U_{norm}^2I_{norm}^2.$$

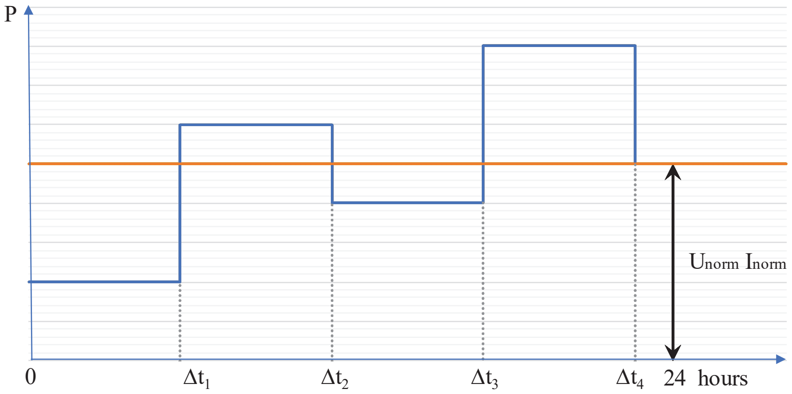

Fig. 1. Daily schedule of consumption relative to the conditionally optimal level $U_{norm}I_{norm}$

The obtained indicator allows to estimate the level of uneven consumption of electricity during the day on the basis of optimal or average values.

3. 6. Optimizing the processes of electricity demand management

Obviously, when DSM mechanisms are implemented, it is necessary to evaluate the demand management performance, which is usually performed on indicators such as [15, 16]:

- the factor of filling the load schedule k_L;
- the total cost of consumed electricity C_e.

Accordingly, it is necessary to apply two criteria, which are presented in the form of objective functions (OF).

The first OF corresponds to the maximization of the load factor of the load schedule kL [32, 34].

$$\max k_L = \frac{\sum_{i=1}^{N}\sum_{j=1}^{J} P_{(i,j)} t_j}{\sum_{j=1}^{J} t_j \sum_{j=1}^{J} P_{(i,j)}},$$

where optimization variables are selected by the power consumption values $P_{(i,j)}$ at time interval t_j (usually the time interval is 1–2 hours) by consumer groups i. Accordingly, the numerator of the objective function represents the amount of consumed power. The OF is linear with respect to the optimization variables. The dimension of the problem is $N \times J$, where N – number of consumer groups; J – the number of time intervals [32].

The second OF is to minimize the cost C [33]:

$$\text{Min } C = \left[\sum_{i=1}^{N}\sum_{j=1}^{J} P_{(i,j)} \cdot t_{(j)} \cdot ce_{(i,j)}\right] + \left[\sum_{i=1}^{N}\sum_{j=1}^{J} P_{(i,j)} \cdot t_{(j)} \cdot cd_{(i,j)}\right],$$

where the OF by criterion Ce – cost of consumed electricity is also linear and represents a minimization of consumed electricity cost. Optimization variables are selected: power consumption over time interval t_j by consumer groups i, electricity tariff Ce, charge for installed capacity cd. The first addition is the charge for the amount of consumed energy, the second addition is the payment for the power.

Optimized schedules of daily electricity consumption are constructed with restrictions in mind [33, 34]:

$$P_{new}(i) = P_{old}(i)_{\forall} t_o \rightarrow t_k, t_h \rightarrow T_D,$$

that is, the total amount of power consumed Pt the T_D time interval remains unchanged and must be constrained at every interval:

$$P_{new}(i) \le P_{(value1)} \forall t_k \to t_h,$$

$$P_{new}(i) \ge P_{(value2)} \forall t_k \to t_h,$$

however, peak consumption from the time interval (t_k; t_h) is evenly transferred to time intervals (t_o; t_k) ∪ (t_h; T_D) (**Fig. 2**).

$$P_{(value2)} \le P_{(value1)},$$

where the constraints of the problem relate to the need to save the total power consumption over the billing period: $P_{new,i}=P_{old}$, and limiting the maximum values of the maximum power consumption: $P_{new,i}<P_{\max}$, arising from network and power system boundary capabilities, such as limited power generation of power system equipment, restrictions on the capacity of the distribution network, transformers, etc.

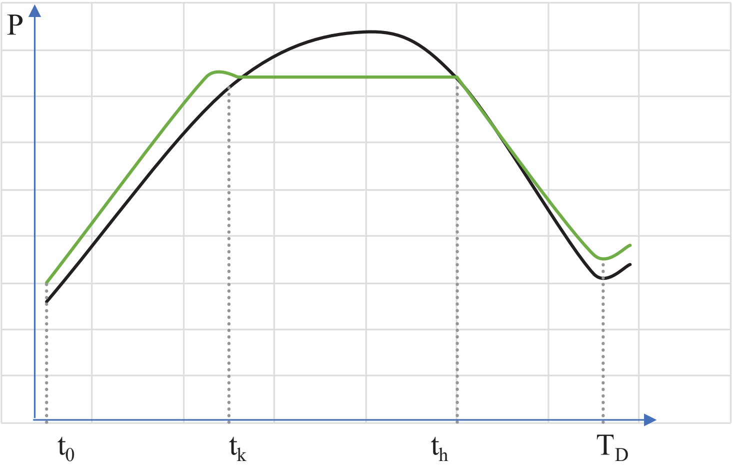

Fig. 2. Illustration of load transfer while maintaining consumption balance

The above description of the optimization problem is somewhat simplified and does not take into account the ability of the consumer to change consumption profiles in automatic mode for different types of equipment. As an example, it is much easier for a household group user to change their dishwasher consumption profile than a lighting system [33]. To consider the ability of consumers to change the level of their equipment consumption, it is necessary to enter the third criterion and formulate an appropriate optimization problem. Idea is minimization of the initial load schedule irregularity degree after DSM application – min F_g.

The peculiarities of consumers are taken into account by the flexibility coefficient of demand k_g, which can take a value from 0 to 1.Value of 0 corresponds to the least flexibility of the equipment, 1 to the maximum flexibility. This coefficient represents the willingness of the consumer to change the consumption profile of specific equipment by shifting consumption to other time intervals [16].

Nonlinear multicriteria optimization problem for OFF$_g$ [33, 34]:

$$\min F_g = \sum_{i=1}^{N}\sum_{j=1}^{T}\left(P_{new}-P_{old}\right)^2 \cdot \frac{1}{k_g},$$

$$\min y = \begin{cases} C(P_{new}) - w_1 \cdot y_1 \le g_1; \\ Cur(P_{new}) - w_2 \cdot y_2 \le g_2; \\ E_{new} = E_{old}; \\ P_{new,i} \le P_{\max}. \end{cases}$$

It is proposed to consider separately the pairs of criteria as being appropriate to the objectives of the consumer and the electricity supply organization [16]:

1) the load factor and the coefficient of irregularity of the graph;

2) reduction of consumed electricity cost and the coefficient of consumption schedule irregularity.

To illustrate the results of the optimization model, a group of one thousand households was selected, with the basic equipment: dishwashers, heating and air conditioning, refrigerators, lighting, cooking equipment and multimedia systems.

In the following, the average power values for typical equipment in this class are discussed. It should be noted that the current two-zone tariff was chosen as the criterion for reducing the consumption of electricity, and the equipment flexibility coefficients were selected from the experience of a number of experts on the use of household appliances. Optimization of the daily schedule was carried out in MatLab.

The resulted optimized curves of consumption graphs for maximization of the fill factor for maintaining the balance of power consumption is shown in **Fig. 3**.

The resulted optimized curves of consumption graphs for maximization of the fill factor without maintaining the balance, i. e. it is theoretically possible to switch off the devices during peak consumption hours is shown at **Fig. 4**.

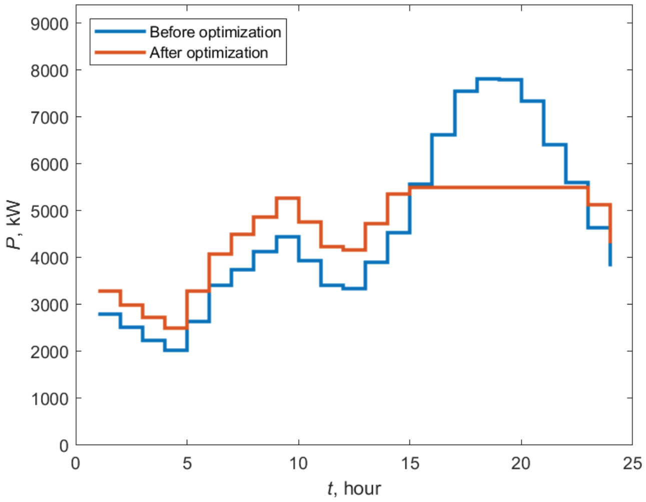

Fig. 3. Results of households daily schedule optimization in case of maximization of the fill factor for maintaining the balance of consumed electricity

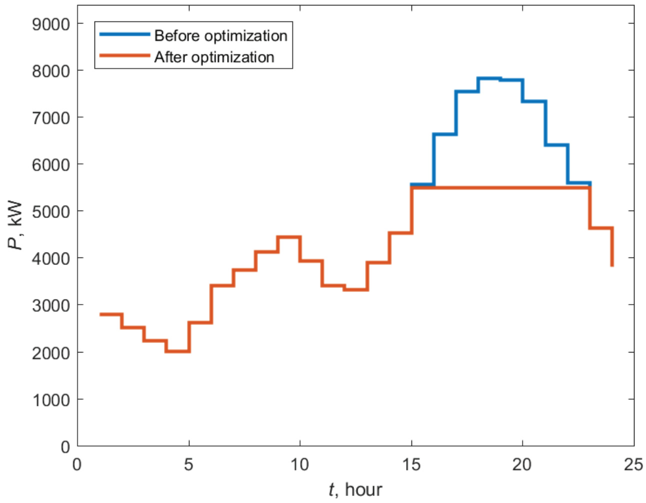

Fig. 4. Maximizing the fill factor without maintaining the balance of electricity consumed

The resulted optimized curves of consumption graphs for minimizing costs while maintaining the balance of electricity consumption is shown at **Fig. 5**.

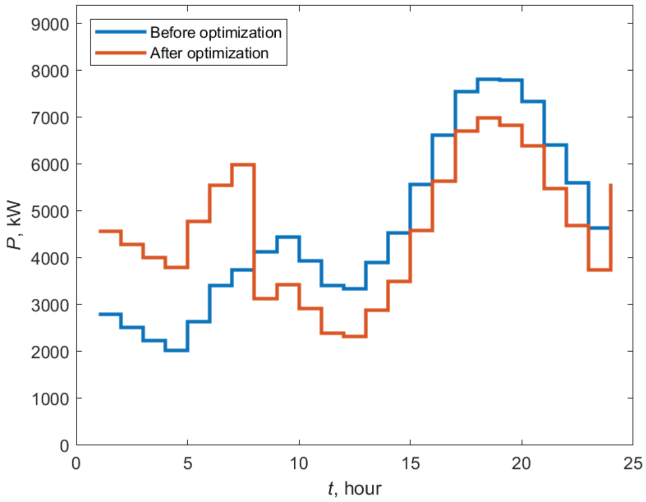

Fig. 5. Minimizing costs while maintaining the balance of consumed electricity

Optimization of the fill factor, which in this case is ideal example of reducing peak consumption, is in practice unattainable, since an important requirement for DSM programs is to balance the benefits gained and the deterioration of consumer comfort. Unlike optimization of the consumption schedule in case of maximization of the fill factor without maintaining the balance (**Fig. 3**) and minimizing costs while maintaining the balance of consumed electricity (**Fig. 5**) are the most attractive for consumers of electricity, since they directly benefit from changing their own mode of operation electricity consumption.

Table 1 shows the numerical values of the received Q_F's on funds and the coefficient of the graph fill before and after optimization, also shows the change in the value of their numerical values.

Table 1

Obtained values before and after optimization

The value of Q_F	Before optimization	After	Indicator change %
Costs C_e	189.6	174.8	7.8
Fill factor k_g	0.587	0.835	29.63

It is suggested not only to use metrics to evaluate optimization results$C$ and k_g, as well as an indicator of loss reduction based on Fryze reactive power Q_F $Q_F^2 = S^2 - P^2$ [31] extended to the daily time interval. In this case, the calculation can be simplified in the case of fully active consumption cosφ = 1 and the calculation of voltage loss as:

$$\Delta U_{\%} = \frac{P_{calc} \cdot R - Q_{calc} \cdot X}{10U_{nom}^2} = \frac{P_{calc} \cdot R}{10U_{nom}^2}.$$

The calculated value of the indicator for the time interval is calculated as:

$$Q_{F,24}^2 = \left(U_{norm}^2 + \sum_{j=1}^{n} \Delta U_j^2 \delta_j\right)\left(I_{norm}^2 + \sum_{j=1}^{n} \Delta I_j^2 \delta_j\right) - U_{norm}^2 I_{norm}^2.$$

Table 2 shows that optimization of operation modes on both indicators led to a decrease in the value of the reactive power of the Fryze Q_F, which is a characteristic reflection of the decrease in the irregularity of the daily schedule of power consumption.

Table 2

Change of Q_F power index for each optimization model

Change of Q_F in case of optimization	Q_F kvar, before	Q_F kvar, after	ΔQ_F (%)
Costs C_e	1817.2	1412.9	22.25
Fill factor k_g	1817.2	980.2	46.1

In conclusion, while constructing the power supply systems with DG sources and Prosumers, one should take into account the generation source types and the variety of their modes of operation.

4. Discussion of experimental results

Obtained optimization results represent the two main optimization of daily consumption. Optimization of the fill factor, which in this case is ideal example of reducing peak consumption and consumer costs optimization can be used as a part of time-of-use program or demand response programs from utility company. 7.8 % of saved cost can be significant as global economic influence, but growing a fill factor by 29.63 % can influence significant in terms of other important factors. Optimizing the fill factor can influence at CO_2 emission reduction as well as energy savings in terms of reducing losses attached to power balancing. Both optimizations can be used at consumers side with IoT and other appliances that can control its own consumption schedule.

Frize indicator Q_F which was used as indicator of «non-optimal» regime while it depends on flat generation-consumption balance, can be used like indicator for local grids operator. The Frize Q_F indicator can simplify impact analysis, but every component of electricity quality must be used according to implemented standards.

It must be noted that such optimization is possible only under DSM programs, as its main idea is to prevent additional generation starts to maintain demand by reducing consumers demand by reducing participants cost on electricity.

Today's households can't schedule their home appliances for a day ahead, but liberalized electricity markets and modern control technologies will bring such cases in nearest future. But even now, with the possibilities of two zones tariff system, a lot of consumers prefer to use dishwashers and laundry in night time.

5. Conclusion

1. Conducted analysis of the processes in power supply systems with DG sources and Prosumers shows that number of different criteria can be united under Q_F power indicator.
2. Obtained optimization criteria $k_{\Delta opt} = Q_F / P \to \min$ can be used for power supply systems with DG sources and Prosumers uneven regimes optimization.
3. Extended Q_F definition to estimate the level of uneven consumption of electricity during the day on the basis of optimal or average values.
4. Presented optimized electricity consumption profiles for household in case of DSM programs implementation shows nice results. There is 29.63 % for fill factor optimization with Q_F reduction for 46.1 and 7.8 % for costs saves with 22.25 % in Q_F decrease.

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