Energy demand side management in stand-alone power supply system with renewable energy sources

Y L Zhukovskiy¹, A Yu Lavrik¹ & A D Buldysko¹

¹ Saint-Petersburg Mining University, 2, 21st Line, St Petersburg 199106, Russia

E-mail: Lavrik_AYu@pers.spmi.ru

Abstract. The article presents the demand side management for electricity consumption in the conditions of autonomous power supply systems with several sources of generation – traditional and renewable energy sources. The paper gives a classification of household electrical appliances in accordance with this, even devices with a high priority, which are often referred to as non-shiftable load, can participate in the program. An algorithm for the interaction of the demand side management control system and the user is proposed. It is shown that with the participation in the demand management program even some types of equipment can achieve a significant economic effect, increase the service life of the equipment and reduce the negative impact on the environment.

1. Introduction

Currently, renewable energy sources (RES) are widely used in decentralized power supply systems in Russia [1]. The use of renewable energy allows to solve many problems – to reduce the cost of electricity generated by diesel power stations (DPS), to increase the reliability of power supply, to reduce the negative impact on the environment [2–4]. At the same time, renewable energy integration has its drawbacks, the main of which are the instability of generation and the difficulty of accumulating the generated electricity [5].

To increase the installed capacity utilization factor, reduce the electric power dissipated at the ballast load, and generally increase the integration of renewable energy sources into power supply systems, there are several technologies, one of which is the Demand Side Management (DSM). Demand regulation involves economic incentives for users to change their load schedule depending on the situation in the power supply system. In relation to autonomous electrical complexes with RES, this situation is characterized by the generation of renewable energy sources, as well as the current level of energy consumption.

There are various ways to implement a DSM system. The most common way – in which electrical appliances are connected via a local network to a power consumption controller installed in the house. In turn, it is connected to a central load controller that serves of many objects. [6]. Together with, there are other methods that exclude, in particular, communication channels, and based on the principle of determining whether the device can be turned on by a controller that monitors the line frequency [7–9].

An important issue is also the classification of devices and methods of user interaction with the control system. These issues are considered, for example, in works [10–12]. A classification of electrical appliances is presented in [10], in which a high-priority load (for example, an electric stove) refers to an unshifted load. At the same time, the potential of DSM in autonomous systems, which
operate, as a rule, with significant operational fuel costs, must be disclosed in the entire available volume. In the study [11], a high-priority load, including kitchen appliances, was classified as a shifted load, despite the lack of a description of the user-DSM interaction algorithm. Accordingly, in this work, a classification and scheme of interaction between DSM and the user is proposed, which provides for the sending of operational notifications by the latter for devices of the selected category.

2. DSM regulations of operation for domestic load
The proposed DSM is based on the system of notifications by users of the electric grid company of the intention to use certain devices. Notification types are described in section 2.1.

Section 2.2 contains the key DSM parameters that characterize the time limits for giving and canceling notifications and power cycling.

It is proposed to classify household electrical devices according to planning flexibility into 4 groups, which is described in detail in section 2.3.

Section 2.4 shows the types of bonuses and penalties charged to provide economic incentives for consumers to warn and change their load schedule.

The algorithm clarifying the operational principle of DSM for using third-group electrical appliances is given in section 2.5.

It should be noted that the developed system does not provide for limiting the supply of electricity to consumers, which would lead to a significant decrease in comfort. Thus, the user is guaranteed to be able to apply any device within the capacity stipulated by the standard contract with the electric grid company.

2.1. Consumer Notices
According to the proposed solution, the consumer, participating in the demand management system, must notify the electric grid company about the planned switching-on (and its duration) of devices of group II and III, as well as when switching to the exceeding power mode of the I-group device.

| Notifications       | Advanced          | Operational       |
|---------------------|-------------------|-------------------|
| I, II groups        | III group         |                   |

2.2. Key DSM timing parameters
The main designations characterizing the parameters of the developed DSM are given in table 2.

| Example |
|---------|
| 24 hours|
| 1 hour  |
| 10 min  |
| 10 min  |
a device of group III is sent

\( t_{d2} \) The time during which, after the scheduled event, the device of group I, II must be switched on

20 min

\( t_{d3} \) The time during which, after the scheduled event, the device of group III must be switched on

5 min

\( t_{c2} \) The minimum time before the scheduled event of use of the device, when it possible to cancel the advanced notification

\( T_2 \)

\( t_{c3} \) The time during which notification can be canceled after sending

15 sec

2.3. Classification of household appliances

It is proposed to classify household appliances according to planning flexibility into 4 groups.

Group I – electrical load, in the normal mode partially controlled by the central management system (hereinafter – CMS). Such a load includes an electric storage water heater.

Group II – low-priority high-power electrical load, i.e. generally portable without significant damage to user comfort. Such a load includes a washing machine, dryer and dishwasher, iron or steamer.

Group III – high-power electrical load with high priority. This group includes an electric stove, kettle and some other powerful, mainly kitchen appliances.

Group IV - low-power electrical load with high priority. This group includes lighting devices, computer equipment, TV and other multimedia equipment, etc.

The classification of household electrical equipment is given in table 3.

Table 3. The proposed classification of household appliances.

| I                  | II               | III               | IV               |
|--------------------|-----------------|------------------|-----------------|
| Partially-controlled CMS | Low priority | High priority |                  |
| Electric water heater | Washing machine | Electric stove | Lighting         |
| Air conditioner    | Drying machine  | Kettle           | Computer         |
| Dishwashing machine | Other           | TV               |                 |
| Iron (steamer)     | Other           |                  | Other            |
| Vacuum, cleaner    |                 |                  |                  |

2.3.1. Group I

To maximize the effect of Demand Side Management, electric water heaters should be partially controlled by the CMS, although this is not an indispensable condition. In this case, the CMS will be able to issue a command for an earlier switching-on of the device in case of excess electricity from renewable energy sources.
To determine the allowable time of advanced switching, at which, despite the heat loss, an economic effect will be achieved, the user must enter the device information into the information data system of the CMS. To do this, a filled water heater connected to the water supply system is switched on to heat water to a maximum temperature, after which the user sets the minimum water temperature according to the instructions of the device, and then fixes the time until the heater is switched on again (in the absence of hot water flow). Data on the tank capacity is entered into the information data system at a time when the user is connected to the DSM system or a new water heater is installed: maximum $T_{\text{max}}$ and minimum $T_{\text{min}}$ temperatures, according to the instructions, and cooling time of the water in the tank temperature from $T_{\text{max}}$ to temperature $T_{\text{min}}$.

In a routine mode, the consumer sets the time range during which the water heater must maintain the water temperature $t_1$ in the storage tank. By advanced notification from the consumer to CMS, the water heater heats the water to temperature $t_2$ by a certain time.

It should be noted that the water heater, at the user’s request, can be removed from the partial control mode of the CMS. In this case, as well as when implementing a simpler scheme without partial control of the water heater, the water heater is assigned to group III.

Group I also includes air conditioning units and other equipment with cyclic interruptible operation.

2.3.2. Group II
For a certain time, for example, 24 hours before the planned use of a device belonging to group II, the user gets the opportunity to notify the electric grid company about the intention to switch on the device and the expected duration of its use.

Not earlier than 1 hour before the pointed-out time, the user may be asked to refuse using the device at the selected time, this offer may be “accepted” or “rejected” in the information system or ignored.

In order to maximize the effect of DSM in the future, with the wider development of the Internet of Things (IoT), it is possible to classify some devices - washing, drying and dishwashing machines into category I, i.e. to devices partially-controlled by the CMS [13]. In this case, the CMS will be able to issue a command to switch on the device with excess RES power. At this stage, we will assume the use of currently commercially available household appliances.

Part of the devices belonging to group II, it is convenient to start with a delay. In this regard, no sanctions are imposed for ignoring the proposal of the CMS (as well as for rejecting it) to transfer the load to the consumer.

According to the proposed algorithm, the developer must determine the minimum time for which an advanced notification is sent, for example, 1 hour. In cases where an advanced notification of the II-group device is sent later than the minimum time, the user is fined. The penalty is calculated based on the amount of electricity required, the presence of excess renewable energy generation and the warning time.

The user is penalized in default of obligations to switch on the device. Under conditions of advanced notification, the user is given a certain time, for example, 15 minutes after the pointed-out time for activate the device.

2.3.3. Group III
Before switching on the electrical appliances belonging to group III, the user through the information data system carries out operational notification of the electric grid company. After information processing, the user may be asked to refuse to use the device at the selected time, this offer should be “accepted” or “rejected” in the information system. Upon “acceptance” of the rejection offer, the user is blocked from the possibility of operational notification of the request for switch on this device for a while. If the required power reserve occurs during the blocking of the sending of an operational notification, the central management center can inform the user through the information system about the possibility of switching on the device.
The consumer may reject the offer of the CMS to refuse to use the device. For the rejection of the offer, no sanctions are imposed on the consumer. The user should not ignore the CMS’s offer to transfer the use of the device, as a penalty is imposed on him. When switching on the III-group device without notice, the user is sanctioned.

If the obligations to switch on the device are not fulfilled, penalties are imposed on the user. Upon operational notification, the user is given a certain time after the pointed-out time by him to switch on the device.

2.3.4. Group IV
The user does not warn the electric grid company about the planned use of electrical devices belonging to group IV – lighting devices, computers and office equipment, televisions and other equipment whose power does not exceed the value determined by the system developer (for example, 700 W).

2.4. Bonuses and penalties for consumers
The functioning of the demand management system is based on the principles of economical motivation for users. Tables 4 and 5 provide information on the types of bonuses and penalties for the implementation of economic incentives.

| Bonus type | Notification type (appliances group) |
|------------|--------------------------------------|
|            | Advanced (I, II)                     | Operational (III)          |
| A          | Well-timed switching-on of the device over the period $t_{d2}$ | Well-timed switching-on of the device over the period $t_{d3}$ |
| B          | Acceptance of the proposal by the CMS to refuse using the device | Acceptance of the proposal by the CMS to refuse using the device |
| C          | Participation in the program of partial system control by devices of group I (only for group I) | – |

| Penalty type | Notification type (appliances group) |
|--------------|--------------------------------------|
|              | Advanced (I, II)                     | Operational (III)          |
| A            | Cancel notification less than time $t_{c2}$ | Cancel notification later than time $t_{c3}$ after sending |
| B            | Switching on the device without notice (or earlier scheduled time) | Switching on the device without notice (or earlier scheduled time) |
| C            | The device isn’t switching on over the period $t_{d2}$ after the scheduled time | The device isn’t switching on over the period $t_{d2}$ after the scheduled time |
| D            | Late notification | – |

2.5. Operational principles of the system
The proposed DSM operation algorithm of the III-group of household electrical appliances is shown in Fig. 1.

![Diagram of DSM algorithm for the III-group of household electrical appliances]

**Figure 1.** DSM algorithm for the III-group of household electrical appliances.

The DSM operation algorithm of the II-group of household electrical devices has slight differences. For example, in terms of canceling a notification: for group III it is allowed no later than $t_c$ after sending. For group II, it is allowed no later than a certain time before using the device.

3. **The potential of the DSM system**

In fig. 2 a load graph of average European home ownership in the absence of a cyclic interruptible load is presented, i.e. devices referred in this work to I and IV group [14].
Figure 2. The load curve of a typical home ownership in the EU without appliances of group I (electric heating, water heater and air conditioning) and group IV.

The notations used on fig. 2 are described in table 6.

| Abbreviation | Device type          |
|--------------|----------------------|
| OS           | Electric stove       |
| TD           | Drying machine       |
| WM           | Washing machine      |
| CP           | Hot water pump       |
| DW           | Dish washing machine |
| RF           | Refrigerator         |
| FR           | Freezer              |

Next, consider an autonomous electrical complex consisting of 100 such households, as well as generating equipment in the form of a photovoltaic station (PVS) with an installed capacity of 200 kW and a DPS.

The load-graph of 100 typical households is shown in Fig. 3. Figure 3 also shows a graph of the production of PVS on a sunny summer day. Solar irradiance data is converted into power output using the Global Solar Energy Estimator model described in [15].
Figure 3. The load curve of 100 typical households (not all groups of devices are shown) and the generation pattern of PVS with installed capacity of 200 kW excluding DSM.

We carry out the transfer of part of the night load to the time range where there is an excess of power of the PVS. In accordance with the proposed algorithm, a shift in the use of devices to an earlier period is allowed for equipment assigned to group I, which are not considered in this example. Thus, the entire load is transferred only in one direction – to a later period. The final load curve is shown in Fig. 4.

Figure 4. The load curve of 100 typical households (not all groups of devices are shown) and the generation pattern of PVS with installed capacity of 200 kW including DSM.

As a result, the amount of electricity that is required to be generated by DPS decreased by 102.2 kWh. Given the specific diesel consumption of 250 g/kWh, which is typical for new efficient diesel-generator units (DGUs), load transfer in this example will save 25.55 kg of fuel. Taking the cost of diesel fuel including the transport costs 50 thousand rubles, the achieved economic effect is estimated at about 18$.

Table 7 shows data on the number of cycles shifted, as well as an example of the possible sizes of bonuses for consumers. As a result, about $11.6 can be transferred to consumers, while the remaining
6.4 $ is received by the electric grid company.

Table 7. The number of shifted cycles of devices operation and bonuses to consumers.

| Device type | Shifted cycles | Bonus B  | Bonus A  | Total in example |
|-------------|----------------|----------|----------|------------------|
| WM          | 74             | 4 cents  | 4 cents  | 5.92$            |
| DW          | 47             | 5 cents  | 5 cents  | 4.7$             |
| OS          | 8              | 6 cents  | 6 cents  | 0.96$            |
|             |                |          |          | 11.58$           |

It should be noted that diesel fuel consumption for the main part of diesel generators significantly exceeds the accepted value. So, the average specific fuel consumption in the Republic of Sakha, Yakutia (Russia), which operates the largest number of DPS among the country's regions, is 400 g/kWh. In this case, the economic effect of reducing fuel consumption increases by 60%. Also DSM potential can be extend by integration of energy storage system [16].

Other advantages that were obtained during load transfer: for example, 2 hours of the motor resource of the DGU were saved, which is now not used in the time intervals from 08:00 to 09:00 and from 15:00 to 16:00.

In addition, the environmental effect should be mentioned. Calculations based on the specific emissions of DGUs show that by reducing the production of DES by the indicated value, the release of 2.1 kg of carbon and nitrogen oxides, hydrocarbons, soot, sulfur dioxide and other pollutants into the atmosphere will be prevented [17, 18].

4. Conclusion

In this paper, a classification of household electrical appliances is proposed, in terms of which powerful appliances with a high priority are placed in a separate category (mainly kitchen appliances, often referred to as unshifted loads). An algorithm for the interaction of the user and the DSM system is developed and presented.

In the considered example with 100 typical households, as well as with PVS with installed power of 200 kW and DPS, the principle of transferring part of the consumers load is shown. As a result of the transfer, an economic effect, an increase in the service life of the diesel-generator unit and a decrease in atmospheric emissions were noted.

The further direction of work is the development of an intelligent DSM control system, based on machine learning methods that predicts users' power consumption and generates a predictive schedule of power generation and load.

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