Enhancing the sustainability of energy networks through the utilization of smart consumers

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Abstract. Dynamic or static stability of electrical networks is maintained not only by the internal energy of the system but also by the utilization of a hot power reserve. In networks that incorporate renewable energy sources, this reserve should be commensurate with the power capacity of the renewable energy sources. However, this leads to an increase in economic costs. Additionally, the integration of renewable energy sources results in a decrease in the dynamic stability of the system due to the unregulated changes in the supplied energy.
The objective of this research is to analyze the potential impact of renewable energy sources on network stability and explore possibilities for enhancing stability through adaptive operation of smart consumers. Renewable energy generation is characterized by temporal and concentration uncertainties, which can potentially disrupt the operation of the energy system.
The primary approach employed in this study involves analyzing the potential influence of various operational modes of smart consumers, both during load commutation and energy source switching.
The main outcome of this work is the development of a smart consumer algorithm. The devised operating principle mitigates the effects of unstable renewable energy operation or uncertain consumer behavior.
Keywords: smart consumer, dynamic and static stability, renewable energy source, energy system

1 Introduction

Currently, the term "smart technologies" primarily refers to technologies that enable efficient monitoring of energy consumption, evaluation of the economic efficiency of consumption, and improvement of the energy balance of buildings and industrial processes [1]. In many cases, smart technologies imply technologies that allow remote or programmatic control of consumer devices with the aim of reducing overall energy consumption [2,3]. One form of optimizing electricity consumption involves reducing peak

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loads on the grid [4]. In this case, the consumption of individual consumers is distributed in such a way that it covers their consumption over time beyond the main load. Various energy storage systems, the utilization of renewable resources, and accumulator power plants, among others, can be employed for these purposes. Additionally, the term "smart technology" also pertains to devices that exhibit low energy consumption while preserving all operational characteristics [5].

Another key advantage of implementing smart technologies, as devices that respond to the condition of the electrical grid, is the enhancement of the system's stability [6]. In energy systems containing renewable energy sources (RES), there is a risk of disrupting the dynamic stability of the grid due to sudden changes in the supplied energy, such as from a solar or wind power station [7]. A sharp increase in the supplied energy from wind power stations, in the event of a sudden rise in wind speed, can lead to system overload, voltage elevation, and consumer burnout. Another potential disruption to the stability of the energy system occurs when there is a sudden decrease in the power output of solar power plants due to increased cloud cover or if a cloud moves in and obstructs the solar power station [8]. In response to such occurrences, the system rapidly injects power from the hot reserve or increases fuel supply to the power station. Shortly thereafter, there is a sudden surge in power as the wind blows the cloud away, and the power station starts operating at full capacity.

2 Materials and Methods

2.1 Introduction to the problem

Every time the load on the electrical system changes, adjustments need to be made to electricity generation. Such changes are not only energy-intensive but also potentially reduce the overall stability of the system [8]. Sudden changes in demand due to unexpected shutdowns of a large number of devices or significant equipment in the network result in an energy surplus. Subsequently, there is a need for a rapid change in electricity generation, even at the expense of sudden steam release in thermal power plants or reactive water discharge in hydroelectric power plants.

An alternative method of managing the power system is consumer-side management. One recently known system, HDO, controlled the demand of certain enterprises during periods of electricity shortage, especially during peak hours. The proposed management system allows for maintaining a constant or slowly varying production mode using a large number of small devices. Furthermore, the proposed management system aims to achieve the optimal (highest) ratio between generated energy and line losses when switching demand from certain customers [9].

This is an intelligent system of devices that intelligently respond to sudden changes in the electrical grid. The mentioned devices must alter their states in such a way as to minimize the resulting changes in the electrical network.

2.2 Power Grid Control Mode with Smart Appliances

We assume that we have a sufficiently large system that encompasses electricity generation, transmission, distribution, and consumption. The aforementioned system can be described by the relationship:

$$S = \{G_{1\dots} G_n, S_1 \dots S_m\}$$

under the condition $n \ll m$;

representing the basic mode of operation.

$$\sum_{i=1}^{nt} G_i = \sum_{j=1}^{mt} S_j \quad \text{or} \quad \sum_{i=1}^{nt} G_i = \sum_{j=1}^{mt} S_j + \Delta_t$$

G_i - power of generator i
S_j - power of consumer j
i, j, - indices
n - number of generators
m - number of main consumers
nt - number of generators operational at time t
mt - number of loads operational at time t
Δ_t - network losses at time t

The inclusion or exclusion of any device or source with much lower power than the network in that area does not have a significant impact on the network operation. The balance between the power of sources and the total consumption, including losses, is achieved through automation or based solely on the internal self-regulating capability of the network (voltage changes in individual nodes).

Problems arise when there is an unplanned disconnection of a large number of consumers, transmission lines, or parts of the distribution network or generators, whose combined power is comparable to or significant in relation to the network power, or its portion (0.05-0.3 times the rated power of network resources) [10].

For example, when 10% of consumers are disconnected, a large amount of energy is suddenly released, leading to a sharp increase in voltage. Often, a problem arises when there is subsequent reconnection, i.e., when, for example, the consumption that was disconnected is reconnected. In this case, the system has to respond twice: 1) a sudden reduction in energy production on the resource side, and 2) a sharp increase in energy production due to increased consumption.

Such a problem occurs more frequently with renewable energy sources (RES). During gusty winds, the electricity production from wind power plants can change. Similarly, in windy and cloudy weather, there are variations in energy production from solar power plants due to shading and exposure of the sun. Since these changes are practically unpredictable, it is necessary to maintain a significant share of regulating power in the grid. Maintaining such energy balancing has a negative impact on energy prices.

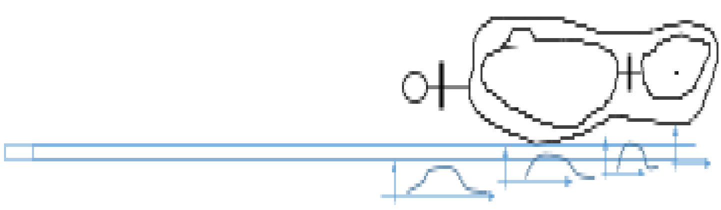


Fig. 1. Network management mode. «Compiled by the authors».

Let's consider an energy system consisting of multiple subsystems as shown in Figure 1. A sudden change in the balance within a part of the system leads to a change in the operating conditions in the main nodes, requiring control of the operating modes of controllable generating stations.

The aim of utilizing smart consumers is to reduce the share of power generation variation. This allows for a decrease in the required hot reserve and a reduction in energy dispersion for overall power adjustments. As a result of the operation of smart consumers, controlled energy sources need to make significantly fewer changes to their operating modes, leading to fuel savings and a decrease in wear on primary power units [11].

2.3 Smart Consumers and Their Operation Modes

To control energy consumption, consumers can be utilized that can be switched on or off at specific time intervals. Such devices include various thermal equipment designed for hot water, heating, refrigeration equipment, and compressed air preparation equipment. Similar devices can also include appliances such as irons, steamers, and coffee makers. The following figures (Fig. 2) depict some curves representing the state changes of the considered devices. Statuses 1i indicate the transition mode from min to max, and designation 2i represents the transition from max to min state. Such a mode can be, for example, heating water in a reservoir and subsequently cooling it to the lower temperature limit. Different devices may have different functions. The graphs shown in the figure represent some selected types**.**

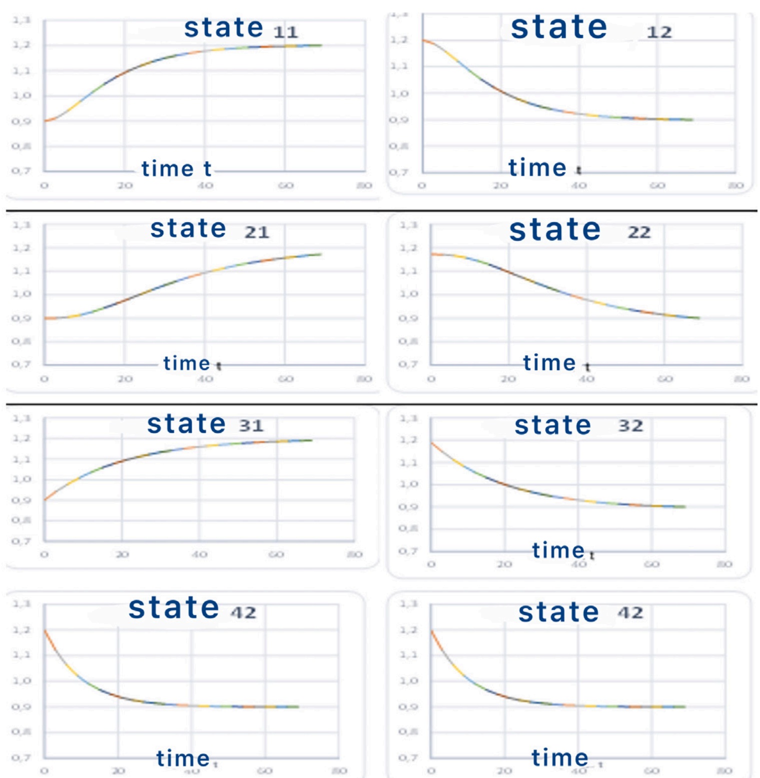
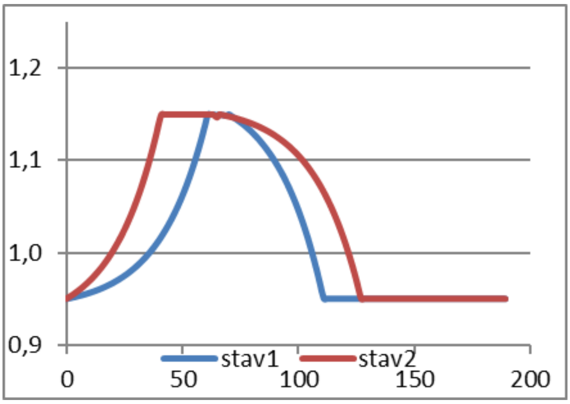


Fig. 2. Graph showing change in consumer state. «Compiled by the authors».

Based on the results of preliminary analysis of several types of devices, it can be inferred that the operation mode of a consumer differs between active usage and relative rest periods. The shape of the start-up and decay curve may be similar, but the slope and rate of change vary. In the graph (Fig. 3), the red curve illustrates the state change during low device usage, while the blue curve represents the period of active usage. Such differences can occur, for instance, when using a water heating device during the early



period when most household members are using water, and throughout the day, there is only natural cooling and reheating to the desired temperature. During this period, the start-up to the maximum value is faster, while the cooling process is slower – resulting in state changes. This increases the available time period for active demand management in switching operations.

Fig. 3. Changes in the status of the consumer across various modes. «Compiled by the authors».

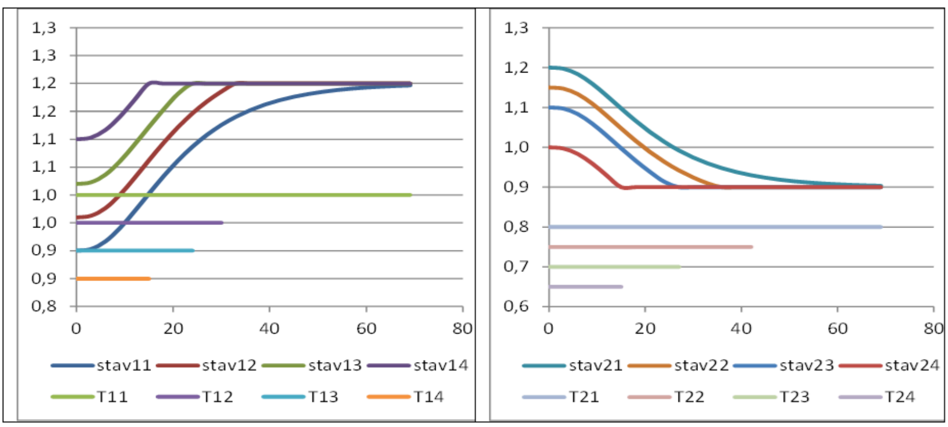


Fig. 4. Consumer state curves under various conditions. «Compiled by the authors».

In the graph (Fig. 4), the curves represent the consumer's states under different consumer activation conditions. The lower part of the graph shows the time interval of consumer activation. By multiplying the consumer's power by the activation time, we obtain the additional energy consumed to improve the system's state during power generation increase. In the right part of the graph, the consumer's deactivation is depicted under different states and with varying intervals of forced disconnection. By multiplying the consumer's power by the forced disconnection time, we calculate the energy saved in the event of a sudden decrease in power generation.

3 Results

The main outcome of this work is the identification of a new type of smart technology operating mode that not only addresses the task of data collection and processing, enabling efficient utilization of the consumer based on this data but also primarily focuses on autonomously enhancing system stability.

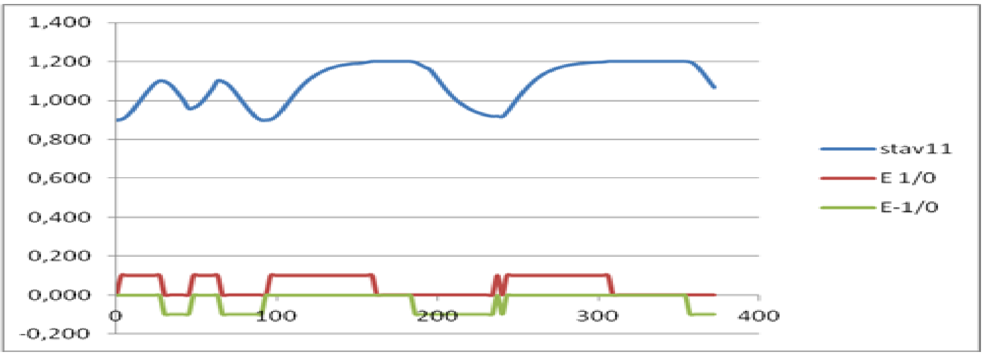


Fig. 5. A graph showing the change in the consumer's state during the network adjustment process. «Compiled by the authors».

The state trajectory of this device is illustrated in the graph (Fig. 5) based on the network's state. The consumer is engaged when the state exceeds the minimum allowable amount. The state curve begins to rise. However, as resource power decreases, the consumer switches off independently, and its state approaches the lower boundary. Device switching can happen again if the network status allows it. If the device is turned off due to the network condition and the minimum value is achieved, it will be turned back on. This mode is cycled through until the maximum state is attained. The consumer gets deactivated when the maximum value is reached. If it is required to reduce total power usage, the next activated consumer will be turned off.

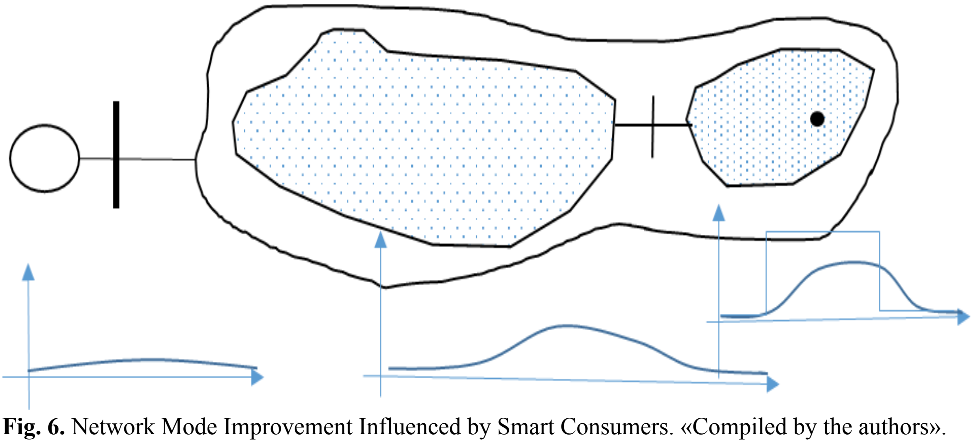


Fig. 6. Network Mode Improvement Influenced by Smart Consumers. «Compiled by the authors».

In the figure below (Fig. 6), an example of the system operation mode using the new type of smart consumers is presented. When the same disturbance occurs, the presence of a large number of smart consumers leads to the smoothing of this disturbance. Devices located near the disturbance mitigate its influence, and devices located further away from the disturbance make the signal to the generating sources even less noticeable. As a result of smart devices, the main generating power units undergo only minor changes in their states.

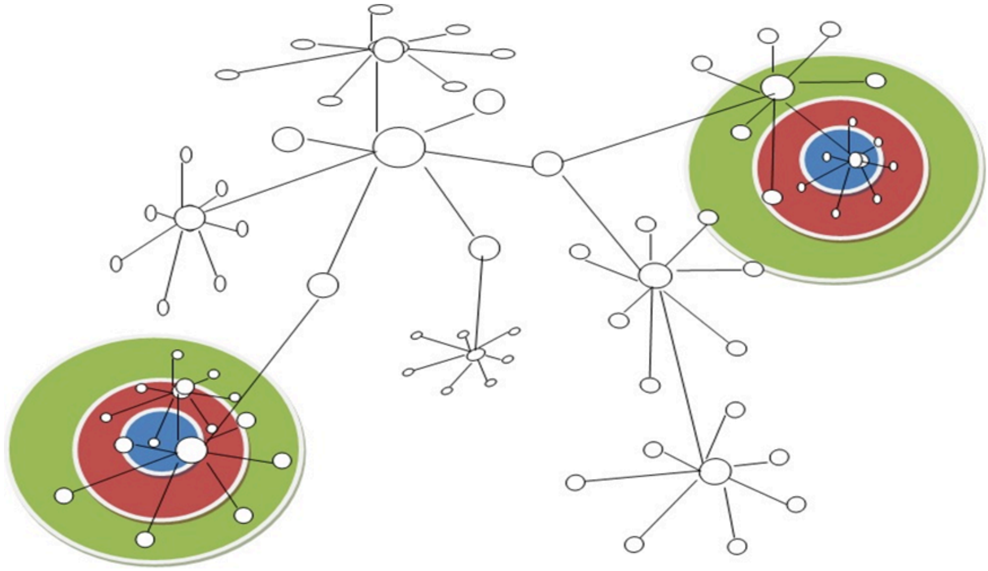


Fig. 7. Smart customers' action zones. «Compiled by the authors».

In the figure (Fig. 7), the zones of disturbance expansion caused by the switching of renewable energy sources (RES) or large consumers or generators are depicted. Thanks to smart consumers, the impact of each disturbance is eliminated in the immediate vicinity of its occurrence, thereby maintaining overall system stability.

4 Discussion

According to research, the intelligent consumer is the consumer who decides on their own what mode they are in in order to better the current status of the network. Their major goal is to ensure a steady supply of energy. Each user has the freedom to choose whether or not to install the essential gadget for their consumers. The installation of such gadgets will have no effect on their experience with these devices. Individual devices can respond to network requests or even detect and react to network state on their own.

5 Conclusion

Based on research, two perspectives on smart technologies in the energy sector can be provided. The first perspective focuses on the capabilities and direction of smart technologies based on the fundamental energy systems of Slovakia and the European Union [12]. These technologies record consumer states, track the amount of consumed energy, the timing of consumption, and provide time-based management. They also facilitate efficient settlement with energy suppliers. By leveraging measurements, a mathematical model of energy expenditure can be created, enabling the development of new consumption models.

The second perspective emphasizes that smart technologies (smart consumers) autonomously operate within the network, improving its parameters in real-time [13]. Both approaches aim to reduce costs associated with the production, transmission, distribution, and consumption of electrical energy, as well as decrease its overall price and enhance the environmental conditions [14]. The outcomes of employing both types of smart technologies also support the use of renewable energy sources and the reduction of energy costs for end consumers.

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