Damping of the Cold Load Pick-up during Hourly Outage Schedules Using Gamification Methods

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Abstract. Main objectives of the study consist in the theoretical formalization and exploratory experimental evaluation of a non-capital-intensive socio-technical demand-side management method designed for damping the parameters of a cumulative charging avalanche that occurs in low-voltage residential distribution electrical networks during scheduled blackout periods of hourly outage schedules. To demonstrate how these objectives were achieved, an analytical mathematical model of load restoration transient processes in time coordinates was synthesized based on the superposition principle and component phase decomposition, a field experimental study was performed on a typical sixty-apartment multi-family residential building with the voluntary deployment of a local demand gamification information loop, and a mathematical calculation of group simultaneity factors was carried out taking into account the integration weight coefficient of individual apartment voltage relays. The most important results are the empirical confirmation of the structural cascade splitting of household energy storage system inverter starting fronts and the controlled time shift of the mathematical expectation of the stochastic socio-behavioral demand phase, which led to a verified reduction in the cumulative peak load of the residential distribution node by 17.0% and a decrease in the recorded maximum current by 27.3 amperes under the combined mitigation scenario, successfully minimizing the risk of accelerated thermal degradation of input fuse links. The significance of obtained results lies in the creation of an efficient, scalable, and non-invasive engineering tool for distribution system operators, the potential integration of which into mobile customer services and automated supervisory control complexes ensures local feeder stability and transformer load profile leveling without expensive modernization of physical equipment and grid cable infrastructure.
***Keywords*:** hourly outage schedules, energy storage systems, Cold Load Pickup, "charging avalanche", cascade decomposition, gamification.

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Atenuarea suprasolicitărilor la pornirea la rece a echipamentelor în timpul unor situații de avarie repetate prin metode de gamificare

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Rezumat. Principalele obiective ale studiului constau în formalizarea teoretică și evaluarea experimentală exploratorie a unei metode socio-tehnice de gestionare a cererii, care nu necesită investiții semnificative de capital și este concepută pentru atenuarea parametrilor unei avalanșe cumulative de încărcare ce apare în rețelele electrice rezidențiale de distribuție de joasă tensiune în timpul perioadelor de întreruperi programate ale alimentării cu energie electrică. Pentru a demonstra modul în care au fost atinse aceste obiective, a fost elaborat un model matematic analitic al proceselor tranzitorii de restaurare a sarcinii în coordonate temporale, bazat pe principiul suprapunerii și pe descompunerea în componente de fază; a fost realizat un studiu experimental de teren pe o clădire rezidențială multifamilială tipică, cu șaizeci de apartamente, prin implementarea voluntară a unei bucle informaționale de gamificare a gestionării cererii locale; și a fost efectuat un calcul matematic al factorilor de simultaneitate ai grupului, luând în considerare coeficientul de pondere al gradului de integrare a releelor individuale de tensiune din apartamente. Cele mai importante rezultate constau în confirmarea empirică a divizării structurale în cascadă a fronturilor de pornire ale invertoarelor sistemelor casnice de stocare a energiei și în deplasarea controlată în timp a valorii așteptate a fazei stochastice a cererii socio-comportamentale. Aceste efecte au condus la o reducere verificată cu 17.0 % a sarcinii cumulative de vârf a nodului de distribuție rezidențial și la o diminuare cu 27.3 A a curentului maxim înregistrat în scenariul combinat de atenuare, reducând astfel riscul degradării termice accelerate a siguranțelor de intrare. Semnificația rezultatelor obținute constă în dezvoltarea unui instrument ingineresc eficient, scalabil și neinvaziv destinat operatorilor sistemelor de distribuție, a cărui integrare potențială în aplicațiile mobile destinate clienților și în sistemele automate de monitorizare și control poate

contribui la creșterea stabilității alimentatorului local și la uniformizarea profilului de sarcină al transformatorului, fără a fi necesară modernizarea costisitoare a echipamentelor și a infrastructurii rețelei electrice.
Cuvinte-cheie: programe orare de întreruperi, sisteme de stocare a energiei, preluare a sarcinii la rece, defecțiuni recurente, descompunere, gamificare.

Демпфирование перегрузок при холодном пуске оборудования во время действия повторяющихся аварий методами геймификации

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Аннотация. Основные цели исследования заключаются в теоретическом описании и предварительной экспериментальной оценке малозатратного социотехнического метода управления спросом электроэнергии, предназначенного для демпфирования параметров перегрузок, возникающих в распределительных электрических сетях низкого напряжения бытового сектора в периоды планового обесточивания при действии графиков почасовых отключений. Для достижения поставленных целей были решены следующие задачи: на основе принципа суперпозиции и фазовой декомпозиции компонентов была синтезирована математическая модель переходных процессов восстановления нагрузки; проведено экспериментальное исследование на базе типичного многоквартирного жилого дома с организацией локального информационного контура геймификации спроса; а также выполнен математический расчет групповых коэффициентов одновременности с учетом весового коэффициента интеграции индивидуальных квартирных реле напряжения. Наиболее важными результатами являются экспериментальное подтверждение структурного каскадного расщепления пусковых фронтов токов и мощностей инверторов бытовых систем накопления энергии и контролируемое смещение во времени математического ожидания стохастической фазы социально-поведенческого спроса населения. Эксперимент позволил снизить кумулятивный пик нагрузки распределительного узла и сократить зарегистрированный максимальный ток в сценарии совместного применения защитных мер, что успешно минимизировало риск ускоренной термической деградации вводных плавких вставок. Значимость полученных результатов состоит в создании эффективного, масштабируемого и неинвазивного инженерного инструмента для операторов систем распределения, потенциальное внедрение которого в мобильные клиентские сервисы и автоматизированные диспетчерские комплексы обеспечивает стабилизацию работы локального фидера и выравнивание графиков нагрузки трансформаторного узла без проведения дорогостоящей модернизации физического оборудования и кабельной инфраструктуры сетей.
Ключевые слова: графики почасовых отключений, системы накопления энергии, режим включения на холодную нагрузку, повторяющаяся авария, декомпозиция, геймификация.

INTRODUCTION

The state of regional power systems under critical operating conditions is characterized by a deep shortage of maneuvering capacity, which is often the result of large-scale infrastructure damage. Significant losses of generating capacity [1] transform hourly outage schedules (HOS) from an emergency response tool into a basic tool for operational demand maneuvering to maintain frequency stability and meet the requirements for the size of flows with the European ENTSO-E power system [2]. The main reason for introducing restrictions is the physical destruction of energy facilities, which makes schedules the only way to maintain the integrity of the network while maintaining centralized control. The desire of the population for a stable energy supply has provoked the mass introduction of household energy storage systems (ESS) based on lithium-iron-phosphate batteries and hybrid inverters [3]. The massive adoption of technology has led to the total installed capacity of household charging stations in crisis-affected regions reaching gigawatt-scale levels, which is equivalent to the capacity of a large nuclear reactor [4]. This gigantic array is completely uncontrolled by distribution system operators (DSOs).

The mass connection of such consumers to the grid after the end of scheduled power supply interruptions has radically changed the classic load recovery profile known as Cold Load Pickup (CLPU) [5, 6]. Traditional CLPU is based on the concept of “loss of timeliness” of thermostatic devices (boilers, refrigerators), which during shutdown experience temperature drift due to thermal memory degradation [7, 8]. When voltage is applied, their simultaneity coefficient approaches unity, generating a spike followed by a smooth exponential decay [9, 10].

However, the mass integration of household SNEs has added a deterministic inertia-free component - the charging current of inverters, configured by control algorithms for immediate forced charging of the battery with maximum current in the DC mode. As a result, the phenomenon of a transformed CLPU (“charging avalanche") [11] arises - a long-term nonlinear state of overload of the distribution network, characterized by the transition of the load graph from an exponential decline to a long rectangular "plateau" due to artificial time compression of daily consumption into a narrow window of light availability.

The rapid development of technologies has led to the mass emergence of prosumers - active subjects of the local energy market. However, as evidenced by the studies of S. Halassi [12], E. Espe [13] and S. Lavrijssen [14] on the behavior of prosumers, an individual optimization strategy (the desire for complete autonomy through energy storage systems) often comes into direct conflict with the global stability of the system. Under such conditions, the transformed CLPU appears as a destabilizing form of prosumer-like behavior: trying to restore its own energy resource as quickly as possible, the consumer creates a critical load on the public network [11].

Peak consumption during power restoration leads to false triggering or thermal destruction of fuse inserts of distribution node protection devices [15]. Mechanical crushing of HOS queues (up to 10-12 subqueues) only exacerbates the problem of energy shortage. In such circumstances, the only alternative descriptive method of peak damping is artificially spreading the time delays of load activation.

The practical application of behavioral demand management methods is based on the Thaler concept of "nudge" [16]. Experience in implementing international programs (in particular, Opower [17] and Oracle [18]) confirms that social comparison tools and interactive visualization of energy consumption volumes provide a stable reduction in peak load within 5–12%. Scientific works by Allcott [19] and Ayres et al. [20] prove that non-cognitive stimulating factors (digital ratings, interactive savings indicators) are more effective in the long term compared to direct declarative or economic appeals. The sociological and practical readiness of household consumers to voluntarily limit power under the threat of system accidents has been verified by representative studies [21] recorded that more than 72% of respondents are ready to adjust the operating schedule of powerful household equipment in the event of a threat of system accidents in the Unified Power System; Recent information experiments on the integration of dynamic mobile notifications [22] about the critical state of the network (game elements with cat characters) demonstrated the possibility of quickly shifting consumption schedules by 3–5% solely due to the behavioral factor, without forced shutdown of lines. Thus, the most flexible tool for the controlled erosion of the social phase (manual demand of residents) are methods of social stimulation and digital gamification.

The purpose of the article is to theoretically substantiate and experimentally verify the method of damping the parameters of the transformed CLPU in the distribution electrical networks of the housing stock during the operation of hourly outage schedules through gamified desynchronization of consumer behavioral demand and coordination shift of technical phases of equipment switching on.

I. METHODS OF RESEARCH

The process of restoring electricity consumption of a residential facility (feeder area) after the completion of scheduled outage intervals of hourly outage schedules loses the signs of a classical stochastic process with a high degree of diversification. As a result of a prolonged absence of power, the states of electrical receivers and behavioral patterns of consumers are synchronized. The situation is further complicated by the transformation of the traditional consumption structure and the mass appearance of prosumers - active subjects of the local energy market. In conditions of power shortage, household prosumers use autonomous systems to compensate for scheduled outage intervals, which radically changes the vector of their interaction with the distribution network: at the moments of outages they act as autonomous power sources, and at the moments of voltage restoration - they instantly turn into active household consumers with a high concentration of simultaneous load.

It should be emphasized that the mathematical formalization of the transformed CLPU phenomenon is currently in its infancy. In this study, the authors primarily followed an empirical trajectory: moving from direct field measurements to the initial attempts of exploratory modeling to mathematically reflect the observed real-world anomalies. Consequently, the proposed system of equations serves as a fundamental analytical framework to qualitatively and structurally describe the process, while the comprehensive development of predictive engineering calculation methods remains a task for future research.

For the mathematical description of the transient processes of the formation of a transformed CLPU, a decomposition method based on the principle of superposition in real time coordinates was used. The total active power $P_{\Sigma}(t)$ of a consumer node is defined as the the sum of independent components:

$$P_{\Sigma}(t) = P_{SNE}(t) + P_{th}(t) + P_{man}(t) + P_{base}(t), \quad (1)$$

where $P_{base}(t)$ – the base load of the constantly switched on infrastructure (standby lighting, communication systems, etc.); $P_{SNE}(t)$ – the charge component of the energy storage systems; $P_{th}(t)$ – the inertial component of the ensemble of boilers and refrigerators; $P_{man}(t)$ – the power of the manual load.

The superposition of these parallel processes, controlled by different technical and behavioral mechanisms, is shown in Fig. 1.

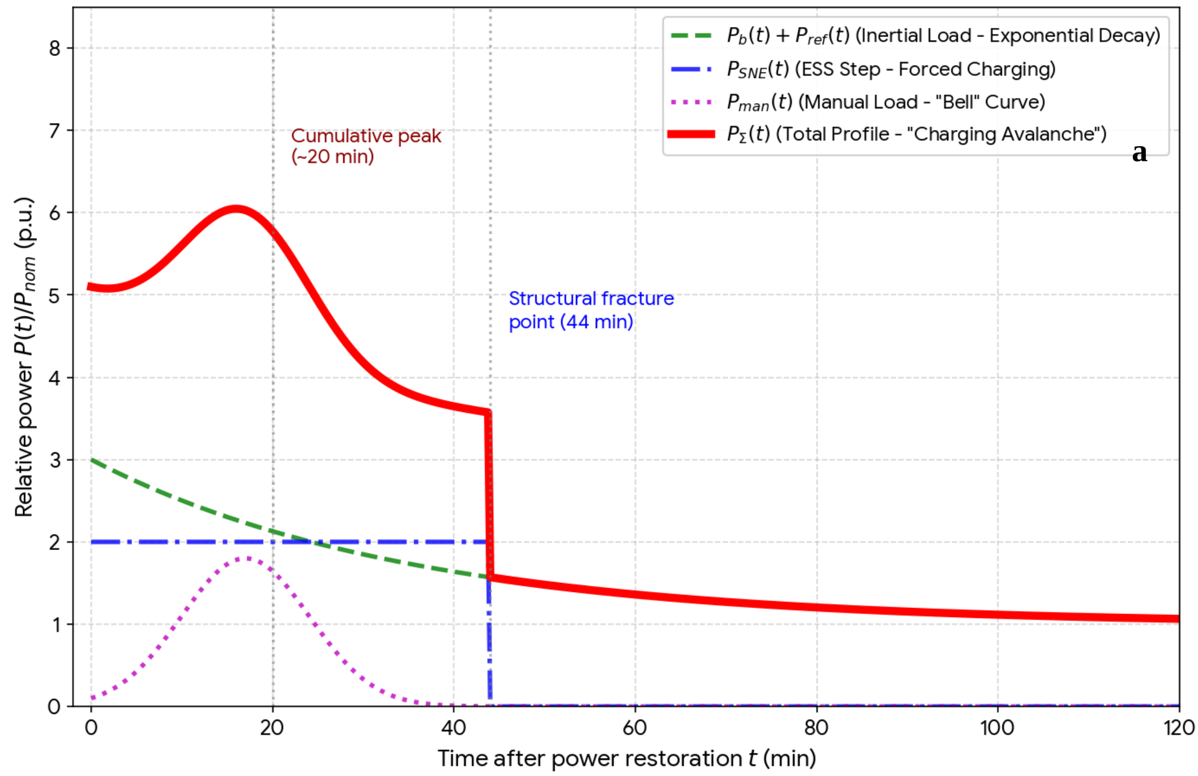

Fig. 1. Illustration of the decomposition of a-transformed CLPU.

To smooth out the peaks of the transformed CLPU without forcibly limiting consumers, the consumption in-phase destruction method was applied. The method consists in artificially spacing the activation delays of different categories of equipment and controlled blurring of the social phase (manual demand).

To ensure quantitative evaluation within the proposed model, the phenomenon of a transformed CLPU is parameterized using two fundamental measured characteristics obtained from the experimental data: the peak amplitude of the overload, which characterizes the maximum surge in active power immediately following grid reconnection and the total duration of the avalanche process, which defines the full time interval from the moment of power restoration until the cumulative load completely decays to the base consumption level.

The practical deployment of the socio-technical contour of in-phase destruction was implemented in the form of a local gamification project a local digital communication channel and community chat of building residents. The contour was based on two interconnected tools:

1. Three-stage dynamic information ("System Traffic Light"). Critical load phase (0...5 min) from the moment of voltage appearance). At this time, a directive notification "Load level: Critical" is sent to the chat. The algorithm instructs

residents about the beginning of intensive charging of the SNE and introduces a strict voluntary ban on turning on heavy thermal appliances (boilers, electric kettles) in the first 15 minutes. Intermediate phase of preventive control (10...15 min), in which the message "Load level: Attention" is published. It informs about the successful passage of the first starting current and requires to keep the delayed demand pause for another 5…7 minutes to consolidate the effect. The phase of full stabilization (15…20 min) with the notification “Load level: Safe” fixes the transition of the node to the green engineering zone, after which all restrictions on manual switching on of large household appliances are removed.

2. System of long-term social stimulation (Digital ranks). To overcome the stochastic resistance of the social environment, residents were assigned long-term digital statuses in the information field of the building residents: “Energy Guard” – a rank for consumers who provided confirmation (screenshot of the settings) of limiting the charging current of their own inverters to a safe level (3…5 A) or set a start-up time delay in the BMS circuit; “Guardian of the Automatic Machine” is a status for setting the technical delay setting for turning on the apartment voltage relay at 300 seconds (5 minutes); “Master of Pauses” is a rank for consumers who unquestioningly adhered to the regulations of deferred demand until permission was received from the “Traffic Light System”.

The combination of the motivational flash mob “Show your 300 seconds” and the weekly publication of the “Morning Board of Honor” made it possible to transform the uncoordinated behavioral factor of the population into a predictable, controlled engineering link. This ensured the displacement of manual demand for an interval of more than 20 minutes, when the initial impulse of consumption had already passed its maximum, which excluded the cumulative addition of capacities.

The transient load profiles were recorded using a NIK 2303 three-phase electronic meter (accuracy class 1.0 according to IEC/EN 62053-21) connected via 160/5 current transformers (accuracy class 0.5S). Cumulative active power data were logged from the display with a fixed sampling interval of 1 minute. This 1-minute interval is methodologically justified as it provides natural low-pass filtering of high-frequency sub-second switching transients, ensuring a clean trajectory of the collective residential load relaxation.

II. RESULTS OF RESEARCH

The description of each component of equation (1) is considered below.

1. The classical inertial (thermal) component is determined by the behavior of household appliances with thermostats (boilers, refrigerators). Due to a long power outage, a temperature drift occurs - the water in the boilers cools down, the refrigerator chambers heat up. At the moment of voltage, all these devices are simultaneously turned on at full power to restore the target temperatures. In the future, this component demonstrates a smooth decrease over several hours as the devices heat up/cool down. This is precisely the manifestation of Cold Load Pickup [5, 6], which is described by the formula

$$P_{th}\left(t\right)=N\cdot d_{th}\cdot P_{nom.th}\cdot K_O\left(t_{off}\right)\cdot e^{-\frac{t}{\tau_{th}}}, \quad (2)$$

where N – the total number of consumers (apartments); d_{th} – the proportion of equipment with thermal devices; $P_{nom.th}$ – the average nominal power of a single device; $K_O\left(t_{off}\right)$ – the simultaneity coefficient, which depends on the shutdown time t_{off}; τ_{th} – the average time constant of the thermal inertia of objects.

2. The inertialess technical component (charging of SNE) is determined by the algorithms of household inverters and charging stations. Unlike thermal devices, battery systems do not have natural thermal inertia and are programmed to immediately consume maximum current when voltage appears in the network. This forms a rigid, rectangular “plateau” of high power, the duration of which depends on the capacity of the batteries and the depth of their discharge. This “plateau” is described by the equation

$$\begin{gathered}P_{SNE}\left(t\right)=N\cdot N_{SNE}\cdot P_{ch.nom}\cdot K_O\times\\ \times\mathbf{1}\left(t\in\left[t_{tech},t_{tech}+t_{SNE}\left(t_{off}\right)\right]\right)\end{gathered}, \quad (3)$$

where N_{SNE} – the level of SNE equipment among the population; $P_{ch.nom}$ – the nominal power of the charger; $\mathbf{1}$ – the Heaviside indicator function; t_{tech} – the parameter of the hardware activation delay;

$t_{SNE}(t_{off})$ – the SNE charging time in the DC mode, which is a function of the shutdown time t_{off}.

In the spontaneous (uncontrolled) mode of operation of the network, which causes the instant start of the entire array of inverters and thermal load with the maximum simultaneity factor $K_O(t_{off}) \to 1$ under the condition of $t_{off} > 4$ hours. According to the methodology of engineering calculations of electrical loads in the residential sector (in particular, by analogy with the regulatory provisions of NCM G.01.02 [23] on demand diversification), the introduction of individual artificial delays t_{tech} in consumer nodes (for example, using a voltage relay) allows desynchronizing the start-up moments, which is equivalent to reducing the simultaneity factor, ensuring a mathematical reduction in the amplitude of the technical peak power.

3. The socio-behavioral component (manual demand) reflects the synchronous actions of residents who, after turning on the light, manually activate small energy-intensive appliances (electric kettles, microwave ovens, coffee makers) or start delayed cycles of washing machines. Due to the natural delay in people's reactions, this demand is distributed according to a lognormal law and forms a pulse in the form of a "bell" with a maximum at 15–20 minutes after power is restored [24, 25]:

$$P_{man}(t) = \frac{K_{comp}}{t \cdot \sigma\sqrt{2\pi}} \cdot \exp\left(-\frac{(\ln(t) - \mu)^2}{2\sigma^2}\right), \quad (4)$$

where K_{comp} is the integral coefficient of the compensatory deferred demand, which integrates the total nominal power of the manual load of the consumer group.

The geometry and amplitude-time parameters of the resulting behavioral "bell" of consumption are determined by two key statistical parameters: μ (mathematical expectation of the logarithm of time) - rigidly sets the time center of the social phase - that is, the median (most likely) reaction time $t_{react} = e^{\mu}$ of the population from the moment when the voltage becomes actually available in the consumer sockets; σ (standard deviation) - reflects the dispersion of the distribution shape, that is, the degree of uncoordinating, individual blurring and dispersion of behavioral consumption habits in time.

The proposed system of time equations (1)–(4) allows us to move from a qualitative description of the transformed CLPU to a rigorous analysis of the interaction of its individual components as functions of time, which creates a mathematical basis for the synthesis of damping algorithms.

To eliminate harmful additive power overlap and ensure operational reliability of networks, a method of artificially spreading the activation intervals of individual load components has been implemented in two agreed directions:

1. Technical decomposition by reducing K_O. Given that some consumers use household network protection using voltage relays, the simplest is to introduce instead of the default settings (3 s) time delays that will be equivalent to the appearance of t_{tech}. If you set the delay $t_{tech} = 5...8$ min using gamification tools, you can shift the initial steep front of switching on the share of the SNE ensemble and inertial load to the right.

According to the logic of demand diversification, artificial dispersion of connection moments transforms the integral simultaneity coefficient of the group $K_O < 1$, reducing the amplitude of the starting current pulse. If the share of households equipped with voltage relays is denoted by α, then it is obvious that under such conditions, at the initial pulse, the simultaneity coefficient will approach

$$K_O \to (1-\alpha). \quad (5)$$

After some time, part of the inertial load is already relaxing, so the new peak of the transformed CLPU will also be less than one.

2. Social decomposition (time shift and blurring). The use of digital behavioral management tools artificially transforms the statistical parameters of the lognormal distribution of manual demand. Due to the information effect, the new mathematical expectation can shift the time center of the social phase to the right ($t_{react} \to 30$ min), and the increase in dispersion makes the behavioral “bell” flatter.

As a result of the implementation of an integrated socio-technical approach, the analytical function of the total power transitions into a time-staggered overlay of individual load components, where the automated ESS demand pulse and the behavioral consumption peak are mutually shifted in time. Due to the provision of temporal non-uniformity, the social behavioral surge is superimposed on the network already at the stage of deep relaxation and decline of the inertial component. The effect of cumulative superimposition is largely leveled.

For practical verification of the proposed socio-technical damping method, a full-scale experimental study was conducted on the basis of a typical residential multi-apartment building. The object of the study was a typical five-story, 60-apartment multi-family residential building constructed in the 1960s, which has the following initial engineering characteristics:

1. Low level of initial implementation of boilers, which allowed minimizing the impact of the classic thermal Cold Load Pickup.

2. The level of equipment with household energy storage systems (SNE) is 18.3%.

To ensure the invariance of the results and the possibility of scaling mathematical models, all consumption graphs are reduced to relative units (RU). The base power value is taken as the average daily power consumption of the house in normal operation mode (in the total absence of power supply interruptions), which for this object is 15.2 kW (which corresponds to a current of 24.3 A). This empirical baseline was verified through field measurements during an identical baseline time interval under normal grid operation without scheduled outages. All current power values are calculated as the ratio of the instantaneous power value to the base value.

During the study, two polar modes of operation of the distribution node were analyzed in detail and compared after the completion of the passive pause of the hourly outage schedules.

During the experimental verification, two characteristic power consumption profiles were recorded and analyzed in detail following the termination of scheduled load shedding periods.

The first scenario (Fig. 2) reflects an uncontrolled, spontaneous transformed CLPU recorded during the baseline field measurements under peak winter load conditions. Here, Pl^{*} represents the total electrical load power of the building, expressed in relative units.

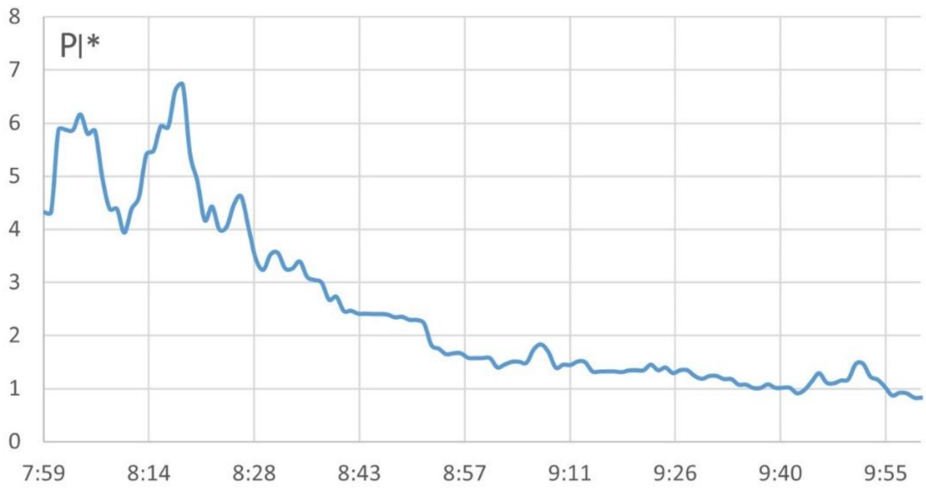

Fig. 2. Experimental graph of a spontaneous transformed CLPU.

This profile illustrates the free start-up of the entire household equipment complex after a long restriction, when any means of technical or socio-behavioral correction were completely absent. The measurement was performed immediately after a five-hour passive pause of de-energizing the line according to the hourly outage schedule, which lasted from 3:00 to 8:00. The dynamics of the transition process within this scenario is characterized by the fact that at the moment of voltage appearance at 8:00, a jump-like inertialess increase in current occurred, caused by the simultaneous transition of the inverters of the energy storage systems to the forced DC charging mode. The manual stochastic demand of residents, who synchronously began to use household electrical appliances, was additively superimposed on the initial rectangular plateau of battery charging, and a clear marker of a trend break and the transition of the inverters to the voltage stabilization mode was recorded at the 44th minute of the process. At the same time, their power was estimated as $P_{SNE} = 0.7$ RU As a result of such an overlap, the cumulative amplitude peak reached a critical value of 6.7 relative units, which in absolute physical quantities corresponds to an active power of 101.8 kW and causes a current of 162.7 A at the input device of the house. An assessment of the engineering consequences shows that this load level exceeded the nominal setting of the input protection of the house, implemented on fuse inserts of a standard 160 A low-voltage industrial fuse. Prolonged maintenance of the current above the critical limit transfers the protection device into the dangerous zone of thermal destruction of the fusible element, creating a high risk of the planned dispatcher switching developing into a long-term emergency situation and large-scale de-energizing of the facility.

The applied analytical decomposition allows for the exact mathematical breakdown of the cumulative peak at the 19th minute ($P_{\Sigma} = 6.7$ RU). At this specific point, the deterministic components are explicitly quantified: the baseline load is P_{base} =1.0 RU, the steady ESS charging plateau contributes $P_{SNE} = 0.7$ RU, and the calculated thermostatic CLPU decay component yields P_{th} =3.11 RU. By executing the subtraction layout (6.7-1.0-0.7-3.11), the net quantitative contribution of the behavioral manual demand is identified as 1.89 RU. This proves that while the socio-behavioral load is not the largest standalone component, its phase-coherent overlay on top of hardware-driven grids acts as the critical catalyst forcing the total system into an emergency overload state.

The second scenario (Fig. 3) reflects the combined damping mode recorded during field measurements under identical grid configuration and operational conditions.

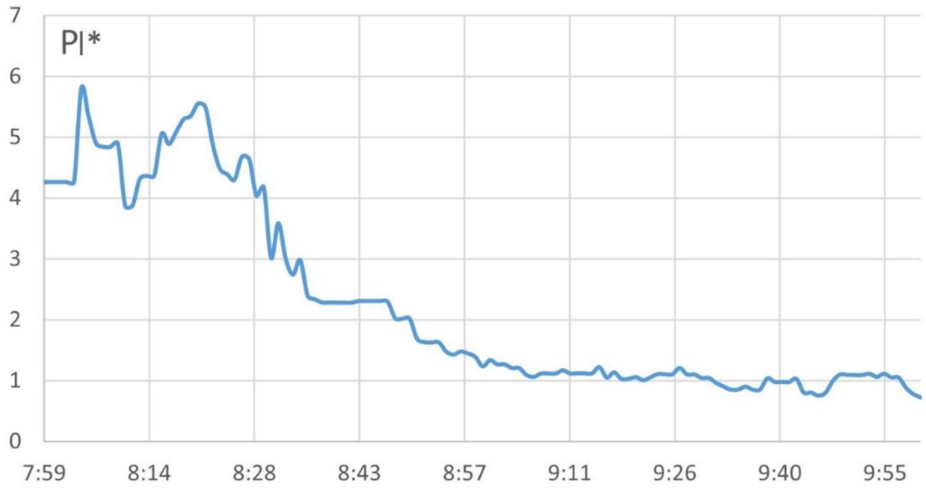

Fig. 3. Experimental graph of a damped transformed CLPU.

This profile demonstrates the house consumption parameters under the condition of the combined and synergistic action of hardware delay means and digital gamification methods of demand within the local building demand-side management system. The measurement was performed after a similar five-hour passive power outage pause from 3:00 to 8:00 under identical consumer operational conditions, however, in this case, the comprehensive approach involved combining the technical setting of apartment voltage relays for a five-minute delay with the simultaneous activation of the "System Traffic Light" regulation in the house chat and the stimulation of long-term digital statuses. During the analysis of the dynamics of the transition process, it was established that thanks to the five-minute delay of apartment voltage relays, which corresponds to the standard of the "Guardian of the Automatic Machine" rank, the house network received the necessary time window for the safe launch of the basic infrastructure and gadgets. Later, due to gamification tools and the residents' fulfillment of the “Master Pause” rank standard, a controlled blurring of the time centers of manual demand activation and their shift to an interval of more than 15–20 minutes was achieved. The behavioral bell-shaped load surge was already superimposed on the relaxation phase of energy storage systems, which completely eliminated the effect of harmful additive power resonance.

The extremum parameters in this scenario demonstrate significant optimization, since the amplitude of the cumulative load decreased by 17% and was fixed at 5.57 relative units. In absolute values, this amounted to 84.7 kW of active power and 135.4 A of load current, thanks to which the parameters of the distribution node were guaranteed to remain in the safe operating zone of a standard 160 A low-voltage industrial fuse link with a reliable engineering margin.

The results of the experiments are summarized in Table 1.

Field experiments have confirmed the high efficiency of the proposed approach. Only the joint implementation of a short-term hardware delay of the voltage relay for 5 minutes and a socio-technical gamification circuit (Scenario 2) provides stable damping of the cumulative peak due to the controlled destruction of the in-phase nature of the technical and social load. This allows maintaining the network parameters within the nominal safe zone without forced consumption restrictions.

Table 1.

Results of the experiments

Distribution node mode parameter	Scenario 1 (transformed CLPU)	Scenario 2 (Gamification)	Efficiency (Sc. 1 to Sc. 2)
Amplitude peak	6,7 RU (101,8 kW)	5,57 RU (84,7 kW)	Reduced by 17.0%
Maximum current	162,7 A	135,4 A	Reduced by 27.3 A
Status of a standard 160 A low-voltage industrial fuse protection device	Melting/fracture zone	Stable working area	Elimination of the risk of an accident
Simultaneity factor	Straight to 1.0 (Common Mode)	0,55...0,6	Effective desynchronization

III. **DISCUSSION**

The anomaly of the uncorrected transformed CLPU, discovered during field experiments, confirms that the widespread uncoordinated implementation of domestic energy storage systems is radically changing the physics of processes in low-voltage distribution networks. The obtained data on the jump in the cumulative load to 6.7 relative units force us to reconsider classical approaches to modeling power restoration modes. Traditional mathematical models of demand restoration, developed in world engineering practice, are based mainly on thermal memory and loss of time-varying devices with thermostats. However, in critical grid conditions, this thermal inertia of boilers has been supplemented by a powerful, algorithmically determined and inertialess factor - the charging current of inverters, which are programmed for immediate forced start in the DC mode. As a result, instead of the classical exponential decay of the current, a long rectangular plateau of high power is observed, which artificially compresses daily consumption into a narrow-scheduled power supply interval availability.

The fixation of the trend break marker at the 44th minute is extremely important, as it indicates the moment of mass transition of the house's batteries from the DC mode to the voltage stabilization mode. This time benchmark proves that the charging current of modern lithium-iron-phosphate batteries keeps the distribution node in a state of severe technical load for almost three quarters of an hour. The greatest danger lies in the fact that it is precisely in this time window that the maximum socio-behavioral demand of residents falls. The free superposition of this behavioral bell on the rectangular technical plateau of the inverters creates a dangerous cumulative resonance of capacities. The avalanche current is guaranteed to transfer the fuse links of the house protection into a mode of prolonged thermal overload. Since this current exceeds the nominal value, the fuse-link begins to accumulate excess heat, which, under conditions of systematic cyclic starts, leads to accelerated degradation of its structural elements, critical heating of the contact blades and significantly increases the risk of false protection operation or its complete thermal damage in the future. This turns planned dispatching switching into a potential emergency situation.

The effectiveness of purely hardware methods of counteracting the transformed CLPU remains a debatable issue. Recommendations to increase the re-activation delay of apartment voltage relays to five minutes, which are often considered as the only solution, actually have limited engineering value if applied in isolation. Within the framework of this study, it was established that since individual voltage relays are installed only in some apartments (weighting factor α), the feeder node undergoes cascade load splitting. A five-minute technical pause by itself does not destroy phase coherence completely, but only mechanically shifts the steep front of the controlled prosumer-like cascade load by the fifth minute. Without a purposeful social phase blurring, the manual population demand still superimposes itself on the unrelaxed part of the inertial load of the uncorrected group $(1-\alpha)$, leaving the amplitude of the cumulative peak higher than the critical limits of the network's thermal stability.

That is why the results of implementing the combined socio-technical gamification circuit open a new vector in demand management research. Involving residents in game interaction through a home chat and implementing a digital ranking system inspired by national experience in the use of interactive digital simulators and non-cognitive stimuli made it possible to transform the uncoordinated human factor into a controllable parameter of the power system. Successful smoothing of the cumulative peak by 17 percent and reduction of current to a safe value became possible not due to forced restriction of people's vital activity, but due to artificial blurring of the time centers of manual demand activation for an interval of more than fifteen minutes from the moment of voltage appearance. In such a configuration, the behavioral surge in consumption was already superimposed on the relaxation stage, which mathematically and practically reduced the power peak and kept the thermal state of protection in a stable operating zone.

The prospects for the development of this approach are of particular importance in the light of the projected trends in the development of the household sector. Given the long-term instability of generation, the further growth of the population's equipment with autonomous energy storage systems has a pronounced exponential nature. Under such conditions, the introduction of methods of digital gamification and socio-technical desynchronization with demand is finally transformed from a local experimental method into a promising engineering fact and a strategic tool for adjusting the parameters of the transformed CLPU at the macro level of distribution system operators. In the macroeconomic dimension, this approach acts as a powerful stabilizing factor that allows regional energy companies to avoid colossal and often prohibitive capital expenditures for large-scale modernization and reconstruction of the physical hardware of low-voltage distribution networks. Instead of an emergency increase in the cross-section of cable lines and replacement of power transformers at 10/0.4 kV substations, operators are given the opportunity to intelligently manage the available network resource through digital coordination of its active agents. The integration of a three-stage information model directly into mobile applications and digital services of regional energy companies, synchronized with SCADA dispatch systems, will allow desynchronizing the demand of millions of subscribers, minimizing the failure rate of switching equipment, and forming a predicted dynamic stability reserve for the entire power system.

In this study, the parameters of the mathematical model (such as τ_{th}, K_O, μ, and σ) were fixed based on preliminary empirical approximations of the field experiment data. A rigorous mathematical framework for the non-invasive identification of these parameters directly from cumulative smart meter profiles constitutes a significant separate challenge. Therefore, the development of specialized algorithms for the non-invasive parameter identification of the transformed CLPU and socio-behavioral demand curves will be comprehensively presented in a dedicated future publication.

Following the exploratory nature of this study, the developed equations were utilized for the structural trend verification rather than precise numerical fitting. The analytical curves derived from the proposed model demonstrate a high qualitative convergence with the empirical profiles, accurately reproducing the steep front of the automated demand, the extended rectangular plateau of the transformed CLPU, and the time-shifted behavioral peak.

Finally, it must be emphasized that the empirical findings and the socio-technical modeling framework presented in this study are preliminary and require further comprehensive validation. Since the field experiment was limited to a single residential node, generalized conclusions regarding the macro-level scalability remain exploratory. A rigorous decomposition of the individual mitigation impacts – specifically separating the hardware-driven voltage relay delay from the behavioral gamification feedback

– constitutes an independent scientific challenge. Consequently, our future research pipeline is oriented toward organizing a series of clean room field testings to simulate an isolated "voltage relays only" scenario. Furthermore, the quantitative evaluation of these hardware limitations and system robust stability under human feedback delays will be mathematically finalized in a forthcoming paper utilizing automatic control theory methods.

CONCLUSIONS

Preliminary findings indicate that the mass implementation of household energy storage systems deforms the classic Cold Load Pickup graph, transforming the standard exponential decay profile into a prolonged rectangular high-power plateau.

A mathematical model of the transformed CLPU-in time coordinates has been synthesized, providing an initial analytical framework to separate the deterministic technical phases of equipment activation from the stochastic socio-behavioral demand, modeled via a lognormal distribution.

Empirical decomposition of the cumulative peak at the 19th minute verified that the non-relaxed thermostatic load and the ESS charging plateau, combined with the phase-coherent overlay of the manual consumer demand, act as the primary catalyst forcing the node into a severe thermal overload zone.

Field experimental trials based on the "Energo-Varta" gamification project demonstrated a promising socio-technical damping effect, showing a cumulative peak reduction of 17.0% (from 6.7 RU to 5.57 RU) and lowering the maximum current by 27.3 A, which effectively minimizes the risk of accelerated thermal degradation of input fuse links.

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