Preconditions and Main Features of EVs Application for Frequency Regulation in the Power System

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Abstract

Power system has to balance the processes of production and consumption of electricity in order to maintain a constant frequency in the grids. Frequency and active power regulation plays a decisive role in providing consumers with electricity of appropriate quality, as well as the economy and reliability of electric power systems operation. Ensuring the high quality of regulation, first of all, depends on the system regulator. In cases where there is a gap between the generation and the load, grid frequency will change and its value will deviate from the nominal. Frequency regulation of power grid is usually performed by power plants, which are controlled by changing the power (increasing or decreasing relative to nominal value). Over the past decade, electric vehicles (EVs) have gotten a significant attention owing to their numerous benefits, such as remarkable energy efficiency, enhanced driving convenience, and reduced environmental footprint The possibility of providing this function with EVs connected to the mains by changing the charging speed based on the frequency of the grid measured at the local level is considered. Given that the number of vehicles connected to the power grid in the world, Europe and Ukraine is constantly growing, the potential for frequency regulation through intelligent control of the vehicle charging process has been investigated means connected to the mains. In addition, in the current conditions of development of decentralized energy supply systems for Ukraine, a significant potential for the use of vehicle-to-grid (V2G) technology has been proven, it consists in improving the efficiency of the centralized electricity supply system through the rational introduction of consumers-regulators based on EVs.

Keywords

frequency regulation, electric vehicles, operation modes, V2G (vehicle-to-grid)

1. Introduction

Modern conditions dictate new requirements, under which reliable and safe operation of the power system of Ukraine must be ensured. For this, at least the commissioning of highly maneuverable capacities with the possibility of quick start-up (turning on from zero and output to nominal power in 10-15 minutes) and high-speed reserves based on electrical energy storage systems will provide the opportunity to provide the Integrated Power System (IPS) of Ukraine with the necessary regulation reserves. However, increasing the flexibility of the power system in this way does not solve the problem of long-term power surpluses, in particular, due to the seasonality of the load. Its solution requires the introduction of power grids from periods of the load schedule, where there is a surplus of energy, to

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periods where there is a shortage of it, as well as the search for new reserves, means and technologies for their application in frequency and power regulation system.

Electrical grids maintain a stable frequency only due to active control of generation and load balance with the help of an auxiliary frequency control service. The frequency of the grid is constantly changing in response to the imbalance of generation and load in real-time. Electrical grids maintain a stable frequency only due to active control of the generation and load balance with the help of an auxiliary frequency regulation service and in the presence of system means to ensure its functioning (dispatching control and high-speed automatic control systems, in particular, automatic frequency and power control systems) [1]. The frequency of the grid is constantly changing in response to the imbalance of generation and load in real-time. In order to regulate the frequency of alternating current within (50±0.2 Hz), without going beyond the maximum permissible limits (50±0.4 Hz), a number of auxiliary services within the electricity market of Ukraine is formed and operates. In Ukraine, the peak load of the power system falls on average for 8 and 20 hours and days. To adjust and pass peak loads, maneuvering capacities of thermal power plants (TPPs), hydropower plants (HPPs) and PSPs in real-time are traditionally used to change the output power between the upper and lower limits. Power plants are usually relatively slow to respond to changes in the desired output power [2], which reduces the quality of regulation provided and often leads to the need to acquire more regulatory power than would be necessary if the response was faster.

Simultaneously, contemporary trends in global energy development and predictions regarding the expansion of renewable energy sources (RES) underscore a profound transformation taking place in the electrical power sector across numerous countries worldwide. This transformation aims to achieve widespread access to cost-effective, dependable, sustainable, and modern energy resources for all. This objective is attained through the active integration and fusion of diverse traditional and renewable energy sources spanning a broad spectrum of capacities, ranging from small-scale distributed generation units to large-scale grid-connected power plants. Ultimately, this undertaking results in a substantial overhaul of power systems [3].

It is noteworthy that in contrast to conventional energy sources, renewable energy generation facilities lack the inherent capability to autonomously ensure the stabilization of frequency and power levels within the power grid. Consequently, variable renewable generation exacerbates grid instability, substantially complicating and increasing the costs associated with frequency and power regulation processes. The adoption of EVs as regulators of frequency and power offers a potential solution, reducing the required financial outlay and offsetting these expenses with the additional benefit of providing ancillary services to the power system. This approach involves the storage of energy in batteries placed in close proximity to consumers, charging these batteries during periods of minimal energy consumption, and discharging energy during periods of heightened demand.

Arranging the entire power grid with batteries is an extremely costly financial project, so until recently, it remained only in theory. With the appearance of EVs and the growing demand for them, this approach has received a new chance for implementation. An electric car can act not only as a means of transportation, but also as a storage device with a significant amount of energy, which can be connected to the general power grid during recharging, or if necessary. Since according to statistics, most cars are not in use for their transport fuction up to 90% of the time, they can become full-fledged participants in the power grid, accumulating energy at the moments of production of excess energy, for example, at night and the return of part of the energy at the moments of peak consumption directly to the grid or to power a particular private building. In this approach, the batteries are as close as possible to the consumer and are a decentralized grid, which makes it impossible to turn them off centrally.

One of the main global trends of the last ten years has been the gradual replacement of vehicles using internal combustion engines with EVs, primarily in order to reduce CO_2 emissions. The growth of the total fleet of EVs in the country makes them a promising part of the energy supply system both at the regional level and at the national level. Due to its capacity and quick response, there is a technical and technological opportunity to use electric vehicle traction batteries to support a number of power grid services, provided that the Vehicle-to-Grid (V2G) concept is created and implemented in the power system. A sufficient number of EVs operating in parallel in the mode of regulation of load and frequency is similar in the mode of operation and the principle of operation at the PSP. Therefore, the implementation of this mode of operation provides economic and environmental benefits for the power system, including the reduction of CO_2 emissions. When combining (aggregating) and managing an organized virtual battery, EVs can provide various ancillary services such as load shifting and frequency control, as well as generally facilitate the integration of renewables.

The purpose of the work **is** to determine how suitable EVs are for use in the frequency control system in the terms of Ukraine.

2. Frequency and power control in Ukraine

In recent years, various pivotal factors have been instrumental in reshaping global power systems. These factors include endeavours to enhance the reliability of power systems and extend energy accessibility through innovative technologies. Furthermore, there is a concerted drive to bolster environmental and climate safety, with a particular focus on the utilization of renewable energy sources in conjunction with heightened energy efficiency measures to address climate-related concerns.

Another significant factor is the substantial reduction in the cost of electricity production and consumption technologies. This reduction encompasses various areas, including wind and solar power generation, distributed energy generation, electric transportation, demand management systems, and energy storage technologies. Additionally, trends towards the electrification of various sectors of the economy, the proliferation of digitalization, and the increased automation of power systems, epitomized by the widespread adoption of the Smart Grid concept, are also contributing to this transformation.

Technological changes require the creation of a base that defines the regulatory, technological and economic rules for the reliable and efficient development and functioning of power systems in new conditions, including the creation of regulatory conditions, as well as the establishment of the practice of planning and operating power systems using intelligent, efficient, reliable and safe technologies. Particular attention should be paid to the fact that with an increase in the share of renewable energy sources (RES) especially wind and solar energy, the share of frequency-sensitive generation in the overall balance of production and consumption of electricity gradually decreases. Therefore, it is necessary to find new potential sources of frequency and power regulation in the power system.

To ensure the safe and reliable operation of the power system, the production and consumption of electricity must be constantly balanced. As the level of renewable energy integration grows, the random or unpredictable nature of renewable energy sources contributes to greater uncertainty in both energy systems and generation. At the same time, the demand for electricity is also marked by a high degree of uncertainty. The most effective method of dealing with uncertainty in the power system is to maintain a certain level of stock or reserve between generating capacity and expected load. Thus, the power system becomes able to effectively cope with uncertainty and unexpected unforeseen circumstances both from the parties and generation and from the parties and electricity consumption. This reserve is called the operational reserve, which is usually provided by specially designated units.

Today, the IPS of Ukraine uses the SCADA/AGC (Supervisory Control And Data Acquisition/Automatic generation control), which is designed to regulate the balance of active power flows on interstate power lines in parallel operation of the UES In countries with power systems of neighboring states, as well as to regulate the frequency in the conditions of its isolated operation by automatically changing the generation of control stations participating in the secondary frequency adjustment. The system has a central regulator (SCADA/AGC), established in the State Enterprise "National Energy Company "Ukrenergo" UES of the country (without the Burshtyn energy "island"). Control actions from the central regulator are transmitted to the dispatching system for regulating hydroelectric power plants, where they are received and processed by station control systems and distributed between hydroelectric units of hydroelectric power plants [4]-[5].

The results of domestic research [6]-[8] indicate that Ukraine has the opportunity to build a complex of automatic frequency and power control (ARCP) as part of the IPS of Ukraine on a fundamentally new basis - on reducing (up to disconnecting) energy use by a special group of consumer regulators. It should be noted that the technological processes of these consumers are organized in such a way that they allow unlimited reduction of electricity consumption for a long time (several hours) at any time of the day or year. Until recently, the opportunities to engage such consumers in the ARCP were very limited due to the practical absence of these technologies with the necessary power and speed. Among the participants on the part of consumers, EVs should be considered as a potential consumer-regulator to maintain the balance of electricity between production and consumption in real-time [9].

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3. Vehicle-To-Grid concept

In Ukraine, in recent years, there has been an increase in demand for EVs, but there are no economic and legal levers to stimulate the use of traction batteries as a maneuverable source, besides, the V2G technology has not been approved at the legislative level, there are no technical requirements for the relevant charging stations, and the grid of standard charging stations is not sufficiently developed to implement this Technology. Thus, the Law 5436-d, adopted in 2022, which regulates electricity storage activities, settled an issue relevant to owners of EVs and a grid of electric charging stations, clearly defining that charging an electric car is consumption, not storage of electricity (therefore, this activity will not require a license). At the same time, this law does not mention the possibility of using V2G technology at all [10], so further development and implementation of this issue at the state level is necessary.

In recent years, the world has successfully used the V2G concept of energy exchange, which provides for the connection of EVs to a common power grid not only for recharging a traction battery but also for transmitting "excessive" electricity of a traction battery to the distribution grid [11]. In fact, the car-grid technology is what allows you to take the accumulated electricity in the battery of an electric car and return it back to the power grid. The main scheme of the V2G concept is shown in Figure 1.

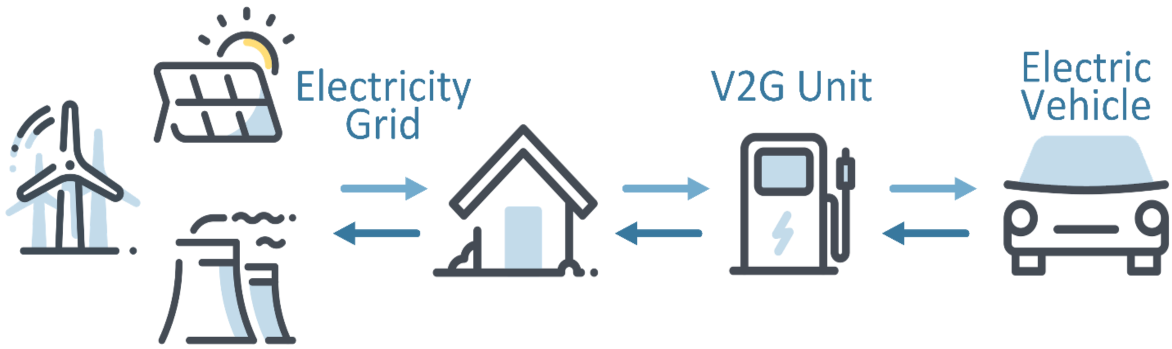

Figure 1: Principal scheme of V2G concept.

It should be noted that the interactions between a vehicle and a grid occur only if there is an interest of the vehicle owner to participate in the V2G system and/or if EVs are widely used in Ukraine. However, EVs as distributed energy resources can also perform distributed storage functions, such as battery banks in people's homes (usually the private sector is most suitable for this), especially with the advent of solar panels on the roof, which is especially important in conditions of stabilization or emergency outages. Nevertheless, an electric car is becoming a real object for taking them into account as energy accumulators in the modern power system, especially considering the fact that a new generation of EVs is being created already equipped with devices for participation in V2G concepts and will immediately be available for use in the grid [12]. Since an electric car battery is a special case of a standard distributed drive, the results of this review can be distributed by analogy on any type of drive that may be suitable for frequency control. In addition, the impact on battery charging and, as a result, on the handling of the car can be used to inform vehicle owners when they make decisions about participating and adjusting the frequency via V2G. The schedule of daily EV operations with the V2G concept is shown in Table 1

Table 1
Modes of daily EV operations with V2G

Time of the day	Operation mode
Morning load peak 7:00 - 8:00	Generator
8:00 - 9:00	Transport
Daytime	Consumer
17:00 - 18:00	Transport
Evening load peak 18:30 - 22:00	Generator
Night time	Consumer

The V2G concept allows to use the energy of the traction battery of EVs and hybrid cars in distributed systems for storing (accumulating) electricity. The traction battery can be used both for energy storage during periods of high level of energy generation in the system and its supply to the grid during periods of low generation. It should be noted that the integration of EVs' electricity into the grid contributes to an increase in the share and use of renewable energy sources and develop microgrids [13]-[14]. In this case, owners of EVs when using V2G have the opportunity to sell electricity to the power system during the hours when the electric car is not in use and charge it during the hours when electricity is cheaper. In many countries (including Ukraine), the cost of electricity depends on time of day and is charged accordingly. The V2G concept is widely developed in the United States (Google, Tesla), Japan (Nissan), Italy (Enel) and other countries.

The main problem for the large-scale use of the V2G concept for the effective provision of the aforementioned services is the limitations on the state of battery power, degradation and battery life. The battery life is inversely proportional to the charge/discharge cycles that the battery goes through during operation. Thus, the charging/discharging operation should be optimized to get the maximum benefit for both EV owners and EV owners grid operator and extend its service life.

The solution is to create a smart charging station for hybrid cars and EVs with a built-in power control, monitoring and balancing device [12]. This development is connected to an external public power grid and an electric car or a hybrid car. At peak moments of electricity consumption, energy to the final consumer comes from the battery of the connected car, and during the hours of lowest consumption, the charge goes to batteries to fill the batteries with a supply of energy for later use in the SmartGrid system or movement on an electric vehicle.

Classic smart grids have the following characteristics [15]:

– ability to manage the work of consumers;
– self-recovery from failures;
– protection from physical and programmatic external interference;
– ensuring power supply of the required quality;
– synchronous operation of generating sources and centers for storing electricity.

The device of the charging station must transmit data of the electric vehicle, such as current strength, voltage, battery temperature, time of departure of the car, permission to use the accumulated energy in decentralized supply systems, agent in control, monitoring and balancing power. Data should also be exchanged with a power agent who provides information on consumption activity energy, the workload of the general grid, the cost of energy consumption and supply by the end user at specified intervals.

For a rational charge-discharge at the station, each car owner must have an appropriate template for using an electric car, where a certain "technological" armour of the residual battery charge level will be reserved, the parameters of which are energy consumption to overcome the distance to the main destination, taking into account the most unfavorable conditions. Justifying the level of such an energy intensity reserve is a difficult task. It should take into account both the technical aspect (topology of available charging points of an electric car, the real mileage of a fully charged battery, etc.) and the human factor (driver behavior, punctuality, accuracy in planning the operation of an electric car). At the research stage, such a reserve can be taken at the level of energy supply of movement from the workplace home, while considering the almost "ideal" mode of using the vehicle. That is, the residual charge should cover the value of the average daily use of an electric car of an individual user.

The use of an electric car battery as a consumer-regulator will cover 50-60% of its cost for 3-3.5 years (1/2 of the normal service life) for household consumers-regulators, after which it will be necessary to replace it. However, over the next three years, in the case of using the spent battery as a decentralized consumer-regulator with a capacity of 60-70% of the nominal, it is possible to obtain a similar additional effect from its use for indirect purposes [16]. That is, for 6-7 years of combined use of the working and used battery, you can benefit from the purchase of a new battery, that is, the most capital-intensive equipment of an electric car for a car owner participating in the regulation of the operating modes of the power system will be compensated by the cost of the generated electricity. In the case of regulation of the gene of the power system at the tariffs of legal entities, the resulting effect for generation will be even greater, and the cost of the traction battery will be covered during the period of basic use of the car's battery and will bring similar profit as a drive.

The transferability of the load of electric transport, a sufficiently high response rate and special characteristics of energy storage make it suitable for the provision of all types of auxiliary services and reserves (as shown in Table 2). With a well-developed market mechanism, EVs as consumer regulators can be an effective source for operational or emergency reserves. Based on these characteristics, special attention should be paid to the need to develop a mechanism for the aggregation of EV, providing operational reserve, as well as a reserve in case of unforeseen circumstances, and its impact on the reliability of the power system.

Table 2

Potential V2G services for different levels of the power system

Power System Level	Services and Benefits	Comments
Generation	Dynamic Balancing	EVs can supply additional power to the grid during peak load periods, providing an additional reserve
	Peak Shaving	EVs can use their batteries to reduce energy consumption during peak load periods, reducing the need for new generating units
	RES integration	When there is excess renewable energy production, EVs can store this surplus electricity, reducing curtailment and energy wastage.
Distribution	Frequency regulation	When the grid frequency drops below the desired level, EVs can inject power into the grid, while they can absorb excess power when the frequency rises, effectively regulating and stabilizing grid frequency.
	Voltage Regulation	EVs can correct high or low voltage levels in the grid, maintaining stability.
	Load Balancing	EVs can evenly distribute loads over time, reducing peak loads and optimizing network operation
Consumption	Energy storage	V2G technology essentially transforms EVs into mobile energy storage. This function can be harnessed into enhancing of Total Grid

		Resilience by offering redundancy and rapid response capabilities during grid failures or blackouts.
	Backup Power	EVs can act as a backup power source for homes and businesses during power outages.
	Additional Services	EVs can provide additional services for consumers, such as charging various devices or even serving as a source of electrical power for household needs.

Through V2G, it is possible to increase operating reserves and reduce energy generation costs. Peak shaving can help reduce fuel consumption during peak load periods and minimize the environmental impact. At the distribution level, voltage regulation and load balancing can enhance the quality of electrical supply. Backup power and additional services for consumers can make EVs more attractive to owners and support grid resilience. As it was mentioned in Tab.1, V2G essentially transforms EVs into mobile energy storage. This energy storage function can be harnessed in various ways, such as Peak Shaving, Load Shifting, Emergency Backup as well as Grid Resilience, when distributed EV batteries offer redundancy and rapid response capabilities during grid failures or blackouts.

In summary, V2G technology presents a multifaceted approach to enhancing the efficiency, reliability, and sustainability of the power grid. These potential services demonstrate the versatility of EVs in contributing to a more integrated, responsive, and robust power system while maximizing the value of EVs to both grid operators and consumers. In addition to storing excess energy produced by RES, EVs can also participate in energy trading, becoming a source of income for its owner to compensate battery cost and degradation through participation in V2G [11]. However, most energy markets in the world (Ukrainian as well) set a minimum capacity for participation (e.g. 1 MW), which requires the formation of an aggregator of a significant number of EVs. With increasing penetration into the electric vehicle market, an electric vehicle aggregator can drive a large number of EVs to provide significant regulatory potential. While EVs can offer effective frequency support, the growing dependence on electricity and the impact of stochastic charging/discharging on power system loads are major concerns of EVs involved in secondary om frequency regulation. As a result, EVs can provide several ancillary services, including rotating reserve, voltage stabilization, energy storage and frequency regulation [17]-[18].

The main aspects that need to be studied regarding frequency regulation using the V2G concept relate to grid stability and saving feasibility. The feasibility of integrating EV into the grid and its role in regulating frequency in the UK power system is analyzed in [19]. Modelling shows that the integration of EV into the grid can stabilize the grid by reducing frequency deviations [20].

4. EVs aggregation

There are several strategies for implementing the V2G concept using centralized or distributed circuits, emphasizing the effective use of EVs for secondary frequency regulation [21]-[22]. In centralized mode, the aggregator controls the fleet of EVs that are located on the charging station. However, EVs are located in public places and are controlled by the grid operator in a distributed mode. In addition, the hierarchical approach uses intermediate levels of aggregation and coordinates the control signal between aggregators and EV to increase the flexibility and scalability of the system. Regulation signals are evaluated at the physical level, which includes a substation unit, aggregators and charging stations. Whereas these adjustment signals are distributed among physical objects at the control level. Charging and discharging strategies are optimized on the basis of mixed integer linear programming [23].

The aggregator should be able to participate in the electricity market through various auxiliary services of the grid, organizing and optimizing the charging of EVs and managing the load profile. The simplified architecture of the V2G system, which emphasizes the role of the aggregator, is shown in Figure 2.

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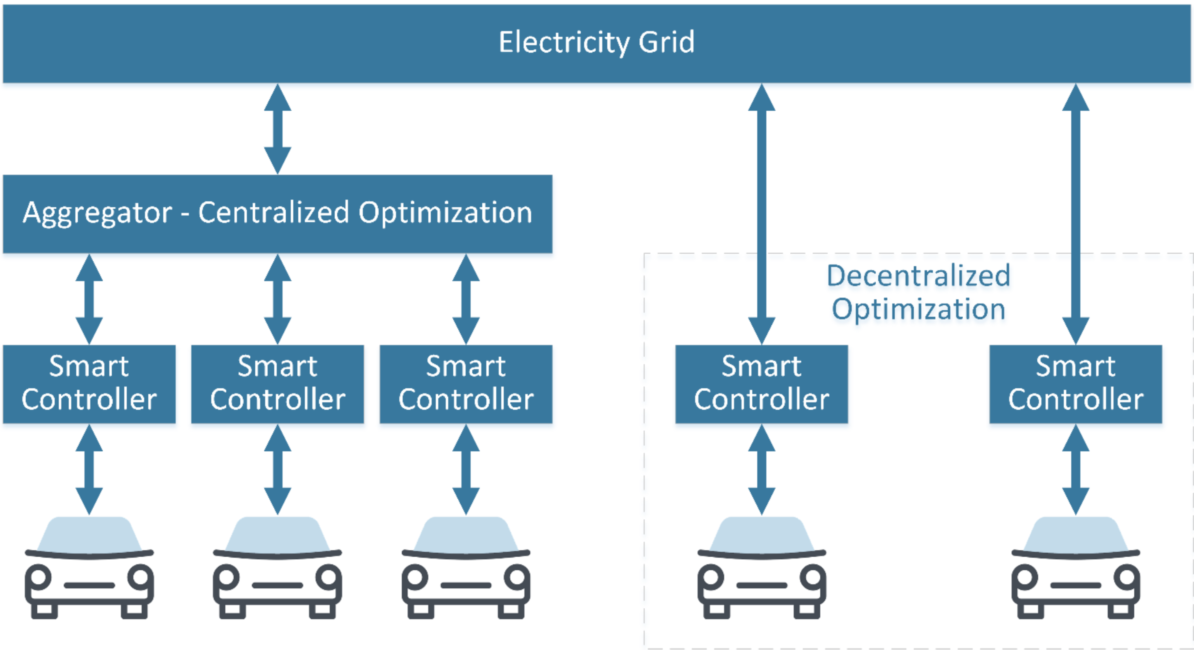

Figure 2: V2G system with an aggregator

Aggregator plays the role of an interface between electric vehicle fleets and grid operators. In the first phase of the process, the aggregator establishes a connection to each vehicle in the vehicle fleet, which has a service contract with an aggregator to use its battery based on its current SOC to participate in grid ancillary services. Data from the electric car will transmit the parameters necessary for the aggregator, the condition for participation in this V2G system is that that the electric car is sufficiently charged during the shutdown time. However, it should be noted that if the driver of the electric car does not comply with the terms of the contract and drives before the previously notified departure time, the battery may not be sufficiently charged during the shutdown. Since the aggregator deals with thousands of vehicles at a time, the proportion of vehicles that depart before the previously notified time will remain constant and is negligible given the regulatory process [24].

As a final step, the aggregator enters into another contract, this time with the grid operator, and determines the type of services and regulatory power that will be supplied to the grid, or the available power required by the aggregator to charge EVs, thus greatly simplifying the task of the grid operator [25].

5. Simulation and results.

Studies of frequency and power stabilization processes with the help of regulators on the basis of HPP and EVs were carried out using the method of equivalent generators for the calculation scheme of the power system, the parameters of which are specified in Table 3 as well as a regulator of a certain type, the calculated power system included equivalent thermal, nuclear and hydropower plants of large capacity, as well as loads and losses in the network. This study was carried out for two work scenarios - the use as a frequency and power regulator of a hydroelectric power plant (HPP) with a capacity of

300 MW or aggregated EVs with the same total capacity of 300 MW and the simulation results are shown in Figure 3.

Table 3
Input data for modelling and benchmarking the use of HPP and EVs with V2G for frequency regulation

Power capacity of the elements of IES, MW						Imbalance at t=0, MW
HPP	TPP	NPP	Load	Losses	Regulator (HPP/V2G)	
2000	9000	11100	20350	2000	300	250

This method and appropriate models were developed under the guidance of Academician Mykhailo Kulik at the General Energy Institute of the National Academy of Sciences of Ukraine [4]-[6], and implemented in the software [7]-[9], and information complex "Frequency-M" [26]-[27]. Features of the implementation of the numerical calculation method allow at each step of the calculation to control the values of all variables for compliance with the nonlinear constraints specified in the model, providing a high accuracy and adequacy of the calculation of transient processes in the power system.

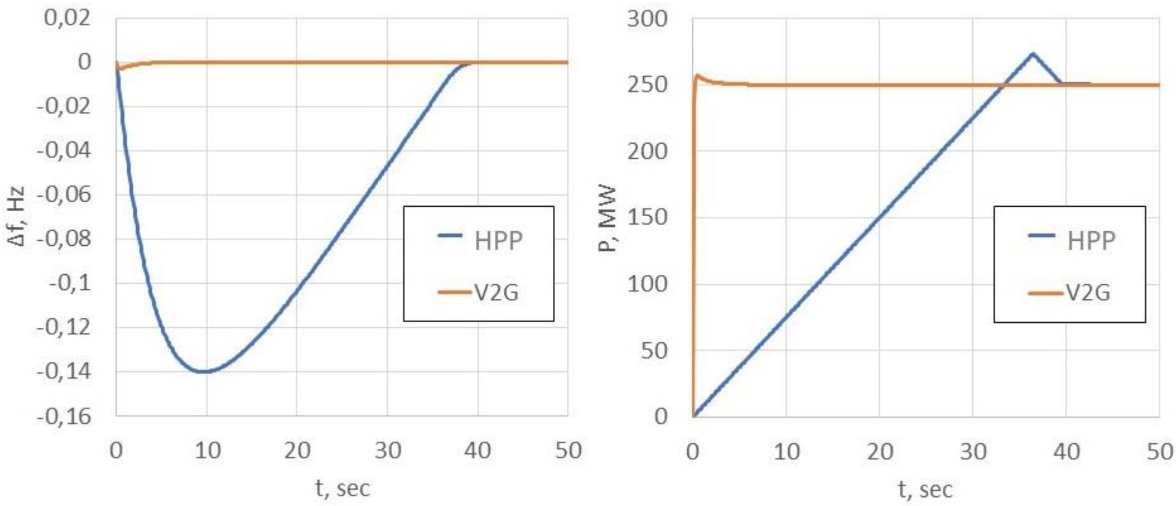

Figure 3: Simulation results of frequency (left) and power (right) regulation in the power system using HPP and EVs as regulators

As it can be seen from the simulation results, EVs exhibit remarkable ability compared to HPPs. As such, they emerge as a highly promising avenue for the regulation of both grid frequency and power within the power system. Traditionally, hydroelectric power stations have been a stalwart resource for grid operators, offering a means to swiftly respond to shifts in electricity demand and generation. However, the modelling results have illuminated that EVs possess a decisive advantage in terms of responsiveness. Their inherent mobility, coupled with advanced grid interaction technologies like V2G, positions them as rapid and adaptable assets.

6. Results/Discussion

EVs are uniquely equipped to expedite grid frequency and power regulation in several ways:

1. Rapid Response Time: EVs can promptly adjust their charging and discharging patterns in direct response to grid signals. This nimble response time enables them to effectively address fluctuations in supply and demand.

2. Distributed Grid Support: EVs are dispersed across urban landscapes, providing distributed support to the grid. This spatial distribution enhances their ability to balance localized power needs, reducing the need for centralized power plants and lengthy transmission lines.

3. Bidirectional Energy Flow: V2G technology empowers EVs to not only draw power from the grid but also inject surplus energy back into it. This bidirectional flow enables EVs to act as energy reservoirs, absorbing excess electricity during periods of high generation and releasing it during peak demand.

4. Frequency Stabilization: By dynamically participating in load-shifting and energy storage, EVs play a crucial role in stabilizing grid frequency. They can absorb excess power during periods of overgeneration and release it when demand surges, contributing to a well-balanced grid.

In conclusion, the modelling outcomes have cast a spotlight on EVs as a swift, adaptable, and forward-looking solution for grid frequency and power regulation. Their innate characteristics, combined with the transformative potential of V2G technology, position EVs as invaluable assets in the modern energy landscape. As Ukraine move toward a more dynamic and sustainable grid, EVs stand ready to meet the challenges of a rapidly evolving energy ecosystem.

7. Conclusions

An overview of the features and prerequisites for the use of EVs for frequency control in the power system was carried out. It was considered about the scenario and charge of EVs using the concept of smart charging V2G. The adjusting ability of EVs aggregation to serve frequency control is closely related to charging scenarios. For EVs with conventional charging, high power adjustment can only be achieved during peak load hours of charging loads. On the contrary, intelligent charging is able to distribute the ability to adjust for most of the time throughout the day Aggregation is one of the best strategies for implementing the V2G concept using centralized or distributed circuits, emphasizing the effective use of EVs for secondary frequency regulation.

The integration of EVs into the power grid has unlocked a spectrum of opportunities for enhancing grid stability, balancing supply and demand, and promoting the integration of renewable energy sources. A comprehensive analysis of the potential of EVs interactions was performed:

Interaction with the Power Grid: EVs can play a pivotal role in load balancing and grid frequency stabilization. The bidirectional capability of V2G technology enables seamless interaction between EVs and the grid.

Integration of RES: EVs have the capacity to harmonize with renewable energy generation. This transforms EVs into mobile energy storage units, capable of absorbing surplus renewable energy and discharging it when needed. This synergy not only promotes the utilization of RES but also mitigates the intermittency challenges associated with renewables.

Interconnection with the Power system: During instances of grid congestion or peak loads, EVs can feed excess energy back into the grid, helping to modulate demand and bolster grid stability. Furthermore, V2G facilitates the return of stored energy to the grid or end user, acting as a reserve or emergency power source. This dynamic interaction reduces strain on traditional power plants and enhances overall grid resilience.

Energy Storage Systems: The batteries within EVs serve as mobile energy storage systems. This dual-purpose functionality not only supports transportation needs but also contributes to grid stability and optimizes energy utilization.

Comparative studies of frequency and power stabilization processes with the help of regulators on the basis of HPP and EVs were carried out using the method of equivalent generators for the calculation scheme of the power system modelling outcomes have cast a spotlight on EVs as a swift, adaptable, and forward-looking solution for grid frequency and power regulation. However, the modelling results have illuminated that EVs possess a decisive advantage in terms of responsiveness. Their inherent mobility, coupled with advanced grid interaction technologies like V2G, positions them as rapid and adaptable assets. As Ukraine move toward a more dynamic and sustainable grid, EVs stand ready to meet the challenges of a rapidly evolving energy ecosystem.

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