Demand-Supply Balancing in Energy Systems with High Photovoltaic Penetration, using Flexibility of Nuclear Power Plants

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Abstract: Energy transition requires scaling up the supply of low emissions electricity from renewable energy sources (RESs) and acceleration of deployment of dispatchable sources of low emissions electricity such as hydro and nuclear. Power output from RESs, particularly photovoltaic (PV) generation, can vary periodically and irregularly, depending on weather conditions. At high PV penetration levels, this peculiarity of the technology can not only cause voltage and power flow fluctuations in the local distribution grids, but also violate the demand-supply balance of a whole energy system, resulting in issues with frequency control and difficulty of demand supply management. This study is primarily focused on demand and supply balancing of an energy system with high PV penetration levels, assuming a significant share of nuclear power plants (NPPs), as well as thermal power plants (TPPs) and a strong transmission system. The potential benefits of flexible nuclear operations in an energy system are analyzed. It is demonstrated that nuclear power plants' flexibility can reduce the share of environmentally unfriendly thermal power units and substantially reduce the restrictions for renewable energy. The IEEE 9-bus test system is used for the case study.

Keywords: nuclear energy; flexible operation; renewable energy integration; demand-supply balancing; transmission power system; nuclear terrorism

1 Introduction

1.1 Global Energy Goals and Challenges

The expansion of solar, wind, and modern bioenergy is particularly significant, while nuclear and hydropower also contribute. Today about 25% of total energy supply is from low emissions energy sources and this expands to around 50% by 2030 in the net zero emissions by 2050 scenario [1]. In the announced pledges scenario, electricity demand increases by 30%, from around 23300 TWh today to about 30300 TWh by 2030, while global CO_2 emissions from electricity generation fall by around 18% in 2030 [1]. Future growth in energy is predicted to mostly come from non-industrialized countries, while for the European Union energy demand is expected to drop slightly. For Asia high growth rates of more than 60% are projected, and the largest absolute boost in energy demand will be observed in China and India [2].

Rapid decarbonization of the electricity sector requires a massive surge in the deployment of low emissions generation. The share of renewables increases from almost 30% of electricity generation globally in 2020 to about 45% in 2030 in the announced pledges scenario [1], but this is still 15% points short of the level reached in the net zero emissions.

Nuclear power and dispatchable low emissions capacity, such as hydropower, biomass and geothermal are important elements of the picture, but capacity additions are dominated by PV and wind. The largest increases in deployment to close the emissions gap take place in emerging market and developing economies [1].

Global energy supply relies predominantly on fossil fuels like oil, coal and natural gas. The most important energy fuel is oil, mostly to fuel cars. Then comes coal, which is primarily used to generate electricity. Third place goes to natural gas, which heats homes, and also generates electricity in turbines. While new sources of energy are gradually changing the energy landscape, the burning of oil, gas, and coal is harmful to the environment. Most prominently, this leads to CO_2 emissions causing global warming. Without further measures, average global temperature will climb by more than 3°C by the end of the century, and sea levels may rise by up to 1 m [2]. To prevent the Earth from overheating, CO_2 and other greenhouse gas emissions must be reduced by at least 50% by the midst of this century, compared to their 1990 levels.

In the announced pledges scenario [1], coal demand declines by 10% to 2030, and almost 85% of demand growth is met by renewables, as a result of which the share of nuclear and renewables increases from 17% to 24% in 2030 and the share of unabated fossil fuels declines to 72% of the global energy mix.

To achieve national policy targets and in response to technological progress, the power sector is expected to go through a phase of significant transformation in most countries. Germany, for example, has decided to switch to a renewable energy economy and leave oil, coal, gas and also nuclear behind. The share of renewables in the power mix in Germany is expected to increase from currently 30% to 50% in 2030 and to 80% in the year 2050 [2]. In comparison, France has decided to reduce the share of nuclear power from the current 75% to 50% over the next 10 years and to increase the share of renewable energies in turn [2].

1.2 Implementation of Energy Efficiency

Energy efficiency implies that more energy services can be generated with the same fuel input, or alternatively, that less fuel input is needed to achieve the same energy service [3]. It reduces reliance on external suppliers of oil and gas and also provides business opportunities for European companies such as construction firms, manufacturers of energy-using equipment or companies selling energy services. For these reasons, the efficient use of energy is also perceived as Europe's biggest energy resource.

Besides saving energy costs, energy efficiency can bring multiple other benefits to households, companies and nations. A recent study by the International Energy Agency finds that improved energy efficiency could reduce the world's energy needs in 2050 by one third at no extra costs, and thus contribute substantially to fight global warming [3]. Projections by the International Energy Agency though suggest that as much as two-thirds of the economically viable energy efficiency potential will remain untapped unless policies change [3].

Consumers, industry and governments all have a role to play in this market. Consumers buy energy efficient technologies and services. Industry invests in research and development to bring to the market energy efficient equipment. Governments invest in policy programs. Indeed, the energy efficiency markets are largely dependent on policies to create the conditions for the market to function. The potential of profitable efficiency measures is huge, but without strong, additional policies, most of it is expected to remain untapped nonetheless, especially in the building sector [4].

1.3 Balancing Operation and Generation Dispatch

To maintain the power balance in a system, it is necessary to schedule the generation of each dispatchable generation unit. The total power demand, which reflects all the changes of all individual demands, varies hourly, daily, weekly, depending on a season and a year. In a power system the balance of demand and supply is ensured by controlling the output of the dispatchable generators in a demand-and-supply balancing area. When the instantaneous balance is insufficient or lost, the power system's frequency (nominally 50 Hz or 60 Hz) or voltage will fluctuate, reducing the quality of supply [5]. In the worst-case multiple devices, including power plants with rotating machines, which are designed to operate within a specified range of frequency deviation, are disconnected from the power system, leading to a blackout (see Fig. 1).

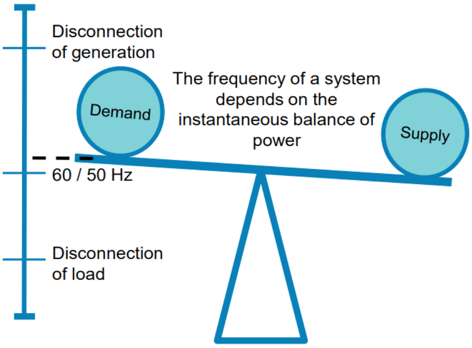

Figure 1
Frequency control in a power system [5]

The balancing between demand and supply is realized through sophisticated generation schedule to make the best use of the features of each generation unit and system: the hourly balancing through generation unit's starts and stops, the balancing in minutes through centralized automatic generation control specifying the production of each unit, the balancing in seconds through independent governor control of each unit, and the remaining mismatch is transformed into a fluctuation of the system frequency [6]. Because the balancing requirements vary by time, by day, by season, reflecting the variation of the demand and supply structure including the share of RESs (e.g., photovoltaic), the key concept to accommodate large amount of variable generation is the flexibility of a power system to cope with the balancing.

1.4 Integration of Variable Renewable Energy

Ukraine has also joined the global course towards decarbonization, development and dissemination of energy-saving technologies and renewables. Recently in Ukraine there is a steady trend for reducing electricity production at pulverized coal power units and increasing the share of carbon-neutral electricity from RESs [7]. One of Ukraine's commitments under the Association Agreement with the European Union is the development and maintenance of RESs, taking into account the principles of economic feasibility and environmental protection. Renewable energy is recognized as one of the main priorities of energy reform, and the promotion of energy production from alternative energy sources is the task of state policy in the energy sector. This is enshrined in the adopted Energy Strategy of Ukraine, for the period up to 2035 and in the provisions of the legal framework. Renewable energy guarantees environmental security and energy independence to the entities that implement it [8].

The United Energy System (UES) of Ukraine is a set of power plants, electrical and thermal networks operating in the general mode of generation, transmission and distribution of electrical and thermal energy. NPPs, TPPs and hydroelectric power plants (HPPs), combined heat and power (CHP) plants, as well as power plants running on alternative energy resources (i.e., solar, wind, biofuel and others) operate in parallel in the UES of Ukraine. All of them are connected by main electric networks. As of mid-2021, the share of electricity generated by nuclear generation is 58.7%, HPPs and pumped storage hydropower – 10.2%, RESs – 9.1%, TPPs and CHPs – 20.5% [7].

Solar energy has received the greatest development among RESs in Ukraine [9]. One of the main advantages of photovoltaics is that due to its modular aspect the size of a system may range from few Watts to several MW or even GW. Another big advantage is that this power production may often be organized directly where it is needed, eliminating most of the transportation and distribution cost. A drawback often put forward is the variability of the power production of solar power plants (SPPs). The PV modules, which constitute the SPPs, can generate electricity during a fairly narrow period of time during the day and demonstrate fluctuations in power production periods due to weather conditions. The SPPs significantly affect the schedule of operation of TPPs, which are the second main source of electricity in Ukraine, along with NPPs. This results in additional costs spent for operation of TPPs. As the installed capacity of SPPs increases, these costs will rise further, and will reduce the efficiency of TPPs in the long run.

NPPs, which account for the largest share of generation, operate on a uniform schedule and create an energy base during the day. NPPs increase or decrease power very slowly, so abrupt maneuvers are simply dangerous. As a result, nuclear power plants cannot increase production during the evening peaks and decrease it at night, when there is a "night dip" in electricity consumption. At the same time, energy share from RESs is growing rapidly, which is a cause for concern. Unlike NPPs, which emit energy constantly and in the same amount, RESs are variable and dependent on weather conditions (i.e., availability of sun or wind) [10] [11]. These are two extremes, and both need to be balanced by those energy sources that can be more easily turned on and off as needed.

The daily and seasonal variability of wind and solar generation present a challenge to their efficient integration into existing electrical grids. In general, the variability and uncertainty introduced by renewable energy calls for a higher level of system flexibility. The amount of flexibility needed to accommodate the introduction of new RESs depends on their capacity and the existing flexibility in the system's infrastructure and operation [10]. This article considers one of the possible ways to overcome this problem – the theoretical possibility of increasing the flexibility of

NPPs. Requirements for the operational stability of energy systems are discussed and highlighted.

The main tasks of the study are as follows:

- Assess the possibility of integrating high levels of variable solar energy without compromising reliability with operational and institutional changes.
- Analyze the impact of unregulated use of SPPs on the modes of electricity generation.
- Estimate the possibility of regulating the operation of the UES with different shares of SPPs in the energy balance.
- Assess the feasibility of flexible regulation of NPPs in terms of power losses and PV curtailment reduction.

Of practical importance is the possible introduction of a mechanism to maintain the balance of demand and supply in the energy system with a significant share of RESs, using the maneuverability of NPPs and TPPs.

The rest of this paper is organized as follows. Section 2 introduces the conditions to maintain the balance of demand and supply of electricity, Section 3 presents the approach to model the power system with NPPs and SPPs, Section 4, defines the case study, and Section 5 provides a discussion of the obtained results and estimates the role of flexible nuclear operations in the energy system. Finally, Section 6 presents the conclusions drawn.

2 Maintaining the Necessary Balance of Demand and Supply of Electricity

2.1 Covering Consumers' Demand of Electric Energy in the UES of Ukraine

The balance of production and consumption of electric energy in the UES of Ukraine is mainly maintained jointly by power units of TPPs and HPPs [12]. At the same time, the maneuverability of HPP power units is usually used during the morning and evening maximums of the power demand. Therefore, the uneven consumers' demand in the UES of Ukraine is predominantly covered with the maneuverability of power units of TPPs. It is impossible to completely exclude at least a part of thermal power units from the daily schedule of load covering in order to reduce their daily starts-stops, because without their participation it is difficult to cover uneven demand through the day, including the maximal demand periods. In addition, TPP power units often remain the only means for regulation of the modes of electricity generation at night [13].

Obviously, the forced use of TPP power units as maneuverable generating capacities of the UES is associated with significant additional costs for their daily start-ups, as well as with costs for the energy generation by these power units [14]. Moreover, this mode of operation is not provided by the design of thermal power units, which leads to the increased wear of equipment, reduced reliability of its operation, as well as increased costs for scheduled and post-emergency repairs of thermal power units [12].

It should also be noted that thermal power units, which are used to regulate the operating capacity of the UES, mostly operate in energy-inefficient modes, especially at night, and their fuel consumption increases. The cost of fuel used in the operation of TPP units with variable load also increases, as the so-called fuel "backlight" (i.e., adding a certain amount of natural gas or fuel oil to the main fuel (coal) to facilitate ignition and ensure sustainable combustion) is periodically required.

The named shortcomings of the forced use of thermal power units as maneuverable generation have a negative impact on the efficiency of the UES of Ukraine, and it is one of the reasons for the increase in wholesale prices and retail electricity tariffs. Thus, despite the significant potential of unloaded generating capacity in the UES of Ukraine, reliable and high-quality energy supply is becoming a challenging task for the energy sector.

2.2 Negative Impacts of Uncontrolled Use of SPPs on the Modes of Operation of TPPs

The need to cover uneven loads is inevitably associated with reduced reliability and efficiency of the power system, the main reason is that in the UES of Ukraine there is a significant shortage of shunting generating capacities, i.e., power units that can quickly go into operation from hot or cold reserve and change the magnitude of their power output in a wide range.

The greatest difficulties in managing the modes of electricity generation in the UES occur during the night demand minimum [15]. These complications are especially noticeable on summer weekends, when consumers’ demand slightly exceeds the base (almost unregulated) capacity of operating NPP units. In this situation, even relatively small fluctuations in consumers’ demand are extremely difficult for the power system. In the event of reduced power demand, it may be necessary to quickly shut down one of the NPP units, which is not only undesirable for economic reasons, but also impossible for technical reasons, as well as in terms of NPP’s safety [16]. In case of a short-term increase in power demand, it may be necessary to curtail some loads or limit their electricity consumption, as the TPPs in reserve cannot be brought into operation quickly enough, and this usually takes at least 1-2 hours. Limiting electricity demand leads to reduction of generation at power plants, which means a reduction of their capacity factor.

The opposite problem is the growing share of RESs in the country's energy balance. If there is an excess of unregulated generation from SPPs in the UAS, while the power demand remains unchanged, the need for electricity production by the thermal power units will decrease. Thus, there will be a need to reduce the output of TPP units or even reserve part of them. It is clear that this will increase the uneven loading of TPP units, significantly worsen their operation modes, leading to rise in costs for their operation and maintenance [12].

Given that, the uncontrolled use of SPPs can gradually exacerbate one of the biggest problems of the UES of Ukraine, which is the uneven daily load schedules of traditional generation, including TPPs. Combined with the shortage of maneuverable generating capacities, this will inevitably decrease the reliability and efficiency.

2.3 Applications of NPP's Flexibility for Maintaining the Balance of Demand and Supply

Increasing the flexibility of generation sources is one of the mechanisms to address the generation variability and ensure the balance of demand and supply. Power systems with increasing penetrations of variable renewable energy sources (i.e., wind and solar power) require greater system flexibility, including operating reserves and ramping capability to ensure that the supply-demand balance is maintained at all times [17-19].

This paper considers the viability of the flexibility enhancing of existing NPPs to allow faster response to demand changes. It should be noted that flexible operation of conventional generators often results in increased fuel, maintenance and capital costs that must be balanced against the benefits of increased levels of renewable energy in the system [6].

NPPs are commonly operated in a “baseload” mode, producing their maximum rated capacity whenever online, while the electricity demand varies during the day and year. In the power system generation must constantly correspond to consumption, and if there are too many NPPs in the system, they will have to change their capacity in response to changes in demand [20]. NPPs are technically capable of more flexible operation, changing their power output over time (i.e., ramping or load following) and contributing to power system reliability needs, including frequency regulation and operating reserves [21]. Flexible operation can help manage daily and seasonal variability in demand or renewable energy output or respond dynamically to hourly market prices or system operator dispatch.

For the UES of Ukraine and for similar power systems with NPPs supplying a substantial portion of the net load and/or with a significant share of variable energy sources, the flexible capabilities of NPPs are essential for maximizing revenues for reactor owners, ensuring system’s reliability, reducing system’s operational costs, integrating renewable energy, and reducing greenhouse gas emissions [21].

However, in literature nuclear units are typically represented as inflexible “must-run” (baseload) resources [19, 20, 22]. These traditional representations do not accurately capture the flexible capabilities of NPPs or the peculiar operational constraints arising from nuclear reactor dynamics and fuel irradiation cycles [21].

For example, pressurized water reactors (PWR), which are common in Ukraine and throughout the world, are capable of flexible operation by adjusting power output primarily by withdrawing neutron absorbing control roads into the core to increase power and inserting control roads to reduce power [21]. The PWR reactor operates in a double-circuit nuclear power system, and ordinary non-boiling water is a neutron moderator and coolant and is under high pressure (~ 16 MPa) [22]. Inserting or withdrawing control rods is an effective way of modulating power output for flexible operation, but the maximum rate at which reactors can adjust electricity production, or “ramp,” is constrained by limitations on the thermal and mechanical stresses incurred by nuclear fuel assemblies.

Depending on the design, French and German reactors can safely operate with ramp rates of up to 2–5.2% of rated power capacity per minute, without increasing the rate of fuel cladding failure [23] [24]. However, in practice ramp maneuvers performed by operators typically proceed at a more conservative pace (e.g., at < 0.5% per minute) to limit stress on reactor components [21]. Existing nuclear plants in France and Germany contribute up to 5% of their maximum rated power to frequency regulation [23] [24].

2.4 Is it Safe to Invest in Nuclear Power?

Nuclear power plants are considered among the safest and most reliable installations in the world. But at the same time, accidents with negative consequences are possible. Today, along with accidents due to technical causes and human factors, nuclear energy engineers must reckon with the possibility of accidents due to military actions. A never known before situation occurred in 2022 at the Zaporizhzhia Nuclear Power Station (ZNPP), in the southeastern Ukraine, which is the largest nuclear power plant in Europe and among the 10 largest in the world.

The ZNPP has become the center of an ongoing nuclear safety crisis, also known as an act of nuclear terrorism by russia, which is considered the most difficult situation of this kind in history [25]. The military forces of the russian federation captured the plant, destructed the power station's infrastructure, damaged its power lines [25]. The potential threat from the development of events may exceed the scale of previous disasters at nuclear power plants [26].

According to the International Atomic Energy Agency (IAEA), the situation in Ukraine is unprecedented, and this is for the first time when an armed conflict continues on the territory of a large nuclear installation [27]. In their report, the IAEA expressed great concern regarding the situation and impact of the military conflict at the ZNPP with respect to operating staff, physical integrity of the facilities, nuclear safety and security systems, communication and power supply [27].

In such a context, nuclear power plants can have threatening consequences for humanity and the environment. Can investing in nuclear energy be considered safe in the 21st century?

3 Regulation and Constraints on Flexible Operation of Nuclear Power Plants

3.1 Modelling of Generation of Different Types of Power Plants

3.1.1 Power Output of Solar Units

As the distributed generation penetration increases, it is necessary to possess generic models of distributed generators and appropriate power flow equivalents, especially in large scale power system models, for which modeling the distribution network is not feasible [28].

In general, it can be assumed that generation in distribution network not modeled in the power flow, but replaced by some combined resultant load and generation (or the sum of both that may results in negative load) may be considered as distributed generation [28]. In this study the modelled SPP represents an aggregated equivalent of a solar PV plant.

The solar irradiation data and the ambient temperature data were extracted from the Photovoltaic Geographical Information System (PVGIS) [29] for the geographical location of Southern Ukraine, latitude: 50°89', longitude: 34°8', as an example. It is assumed that the slope of the PV modules (i.e., the angle with the horizontal plane) is 37° for a fixed (non-solar) mounting type, the azimuth is –1°. The crystalline silicon photoelectric technology is considered. The PV electric output was estimated in accordance with [30]:

$$P_{PV} = \eta_{PV} \cdot A_{PV} \cdot G_{PV} \cdot \left(1 + \gamma\left(T_{PV} - T_{ref}\right)\right), \tag{1}$$

where, P_{PV} is power produced from the PV system in kW; η_{PV} is the power conversion efficiency of the PV module in p.u.; η_{PC} is the efficiency of the power converter in p.u.; A_{PV} is the area of the PV array in m^2; G_{PV} is the solar irradiance incident on the plane of the PV array in kW/m^2; γ is the temperature coefficient of the PV module; T_{PV} is the PV module temperature in °C; and T_{ref} is the reference temperature in °C.

3.1.2 Power Output of Nuclear Units

The output of the nuclear power units is regulated with regard to the ramp rate of the reactors, total power demand and amount of power output from PV installations:

$$P_i^{NPP} = \begin{cases} P_{i-1}^{NPP}\left(1+K_{ramp}\right), & \dfrac{P_i^{\Sigma cons}\cdot\psi}{P_{i-1}^{NPP}+P_i^{SPP}} \geq 1+K_{ramp} \\ P_{i-1}^{NPP}\left(\dfrac{P_i^{\Sigma cons}\cdot\psi}{P_{i-1}^{NPP}+P_i^{SPP}}\right), & \left[1 \leq \dfrac{P_i^{\Sigma cons}\cdot\psi}{P_{i-1}^{NPP}+P_i^{SPP}} < 1+K_{ramp}\right] \vee \ldots \\ \ldots \vee \left[1-K_{ramp} < \dfrac{P_i^{\Sigma cons}\cdot\psi}{P_{i-1}^{NPP}+P_i^{SPP}} < 1\right] & \\ P_{i-1}^{NPP}\left(1-K_{ramp}\right), & \dfrac{P_i^{\Sigma cons}\cdot\psi}{P_{i-1}^{NPP}+P_i^{SPP}} \leq 1+K_{ramp} \end{cases} \qquad (2)$$

In (2) P_i^{NPP} is the instant active power output of the NPP at the i-th time step; P_i^{SPP} is the instant active power output of the SPP at the i-th time step; $P_i^{\Sigma cons}$ is the total instant active power consumption at the i-th time step; ψ is the maximum possible share of NPPs in total energy production in the UES; K_{ramp} is the ramping rate of the NPP in p.u. per a time step. The coefficient ψ depends on the available capacity of nuclear power units and balancing capabilities of the UES and is assumed to be 0.6.

3.1.3 Power Output of Thermal Units

In this the TPP is considered the most maneuverable generation source in the UES, which can cover around 30% of the nominal power demand. Depending on the operational conditions and the load profile, the TPP's output can vary to match the demand and supply. In the model this type of source will be connected to a slack bus.

3.2 Operational Constraints

During the operation of the UES it is important to ensure that system's constraints are satisfied. At each step of the modelling the power system must meet operational constraints, such as power balance, voltage limit at each node, and transmission lines' current capacity limits. In this work the demand and generation values change in hourly steps. To simulate different operating states of the UES, power flow should be recalculated for all the snapshots of load demand values. The constraints are determined as follows [31].

Voltage limits constraints:

$$\left|V_n^{\min}\right| \le \left|V_n\right| \le \left|V_n^{\max}\right| \tag{3}$$

Branch capacity constraints:

$$\begin{aligned} \left|I_{fn}\right| &\le \left|I_{fn}^{\max}\right| \\ \left|I_{rn}\right| &\le \left|I_{rn}^{\max}\right| \end{aligned} \tag{4}$$

SPP real and reactive power constraints:

$$\begin{aligned} P_{\min}^{SPP} &\le P^{SPP} \le P_{\max}^{SPP} \\ Q_{\min}^{SPP} &\le Q^{SPP} \le Q_{\max}^{SPP} \end{aligned} \tag{5}$$

In the equations (3)-(5) V_i is the voltage at the n-th bus, I_{fn} is the forward flow capacity of the n-th branch of the UES; I_{rn} is the reverse flow capacity of the n-th branch of the UES; P^{SPP} and Q^{SPP} are the available real and reactive power capacities of the SPP. The superscripts and subscripts *min* and *max* represent the maximum and minimum allowable limits of the corresponding values. It is accepted in this work that voltage deviations should not exceed ±0.1 p.u. threshold [32].

4 Case Study

The object under study is a UES with a significant share of NPPs, TPPs and SPPs, which in some approximation reminds the simplified energy system of Ukraine and some European countries. The IEEE 9-bus test system with the base 100 MWA was chosen to simulate such a UES. The diagram of the system is shown in Fig. 2.

The modified IEEE 9 bus system was modelled in PowerWorld simulator, and load flow studies were performed to assess the system's performance under different PV penetration levels, using Newton-Raphson method. The rated bus voltages, load values and transformers' impedances are in accordance with [33]. The overhead transmission lines are of 50 km length and have AC-240/32 wires with 605 A current capacity and 217 MW power capacity. The bus data and the rated load data is shown in Table 1, and the branch data is given in Table 2.

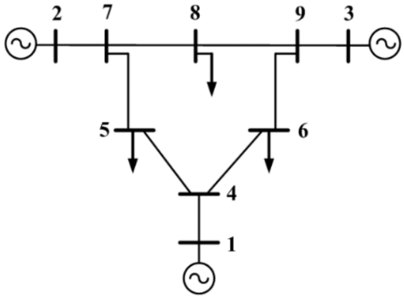

Figure 2
Single-line diagram of the IEEE 9-bus test system

Table 1
Bus data for the power system under study

Bus No.	Bus type	Voltage, p.u.	Voltage, kV	Load	
				MW	Mvar
1	TPP (Slack)	1.04	16.5	0	0
2	NPP	1.025	18.0	0	0
3	SPP	1.025	13.8	0	0
4	PQ	1	230	0	0
5	PQ	1	230	125	50
6	PQ	1	230	90	30
7	PQ	1	230	0	0
8	PQ	1	230	100	35
9	PQ	1	230	0	0

Table 2
Branch data for the power system under study

Line from	Line to	Resistance, R, Ω/km	Reactance, X, Ω/km	Conductivity, B, ℧/km
1	4	0	0.0576	0
4	5	0.121	0.435	$2.6 \cdot 10^{-6}$
4	6	0.121	0.435	$2.6 \cdot 10^{-6}$
5	7	0.121	0.435	$2.6 \cdot 10^{-6}$
6	9	0.121	0.435	$2.6 \cdot 10^{-6}$
7	2	0	0.0625	0
7	8	0.121	0.435	$2.6 \cdot 10^{-6}$
9	3	0	0.0586	0
9	8	0.121	0.435	$2.6 \cdot 10^{-6}$

A single-line diagram of the UES modelled in PowerWorld simulator is shown in Fig. 3.

SPPs are the most unstable sources of the UES with a variable output. Scenarios with the SPPs' installed capacity of 10%, 20%, 30%, 40%, 50%, 75% and 100% of the total system's capacity are considered. The installed capacity of the solar generation units with regard to the total system's capacity is further referred as the penetration level.

TPP power units are maneuverable generating capacities of the UES, and, therefore, they are located at the slack bus, which can adjust its output in wide limits to match the demand and supply.

NPPs are less maneuverable. In the UES of Ukraine the nuclear units usually operate in a "baseload" mode. For the first seven scenarios it is considered that the NPP operates with the ramp rate up to 2% of rated power per a time step, while the installed capacity of SPPs moderately changes from 10% to 100% of the power system's capacity. For the next seven scenarios the NPP power units are considered to have more flexibility so that they are able to operate with the ramp rate of up to 20% per a time step. In this case the NPPs will better contribute to frequency regulation and provision of an operating reserve.

In total, there are fourteen scenarios that differ in the installed capacity of the SPPs and the NPPs' flexibility. Their summary is given in Table 3.

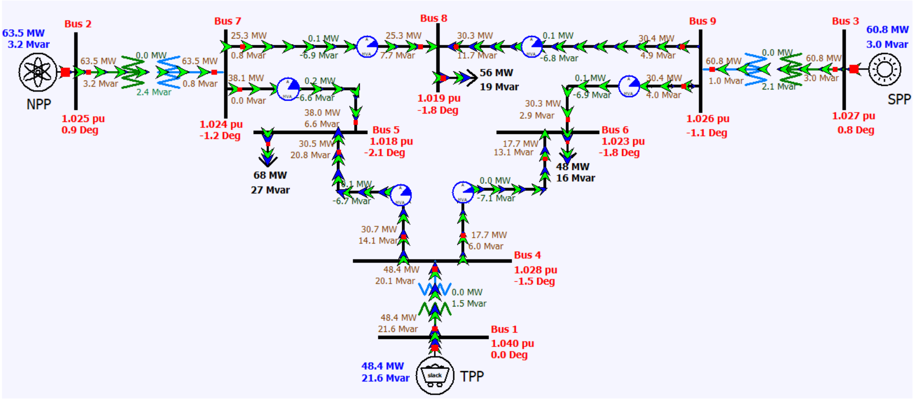

Figure 3

Single-line diagram of the UES in PowerWorld (the simulation is ongoing)

Table 3

Scenarios for the case study

Scenarios	Description
1-7	The installed capacity of the SPPs is 10%, 20%, 30%, 40%, 50%, 75%, 100% of the total power system's capacity. The NPPs have low flexibility and operate with the ramp rate up to 2% of the rated power per a time step.

8-14	The installed capacity of the SPP is 10%, 20%, 30%, 40%, 50%, 75%, 100% of the total power system's capacity. The NPPs have higher flexibility and operate with the ramp rate up to 20% of the rated power per a time step.

5 Results and Discussion

The simulated scenarios are operationally feasible, i.e., power flow converged successfully, and none of the established constraints were violated. The results of the simulation are given in Table 4.

Table 4

Simulation results for different scenarios

Scenario	TPP share, p.u.	NPP share, p.u.	SPP share, p.u.	Power Loss share, p.u.	PV curtailment necessary?	PV curtailment, %
1	41.35	56.29	2.37	0.67	No	0
2	41.70	53.56	4.74	0.65	No	0
3	40.94	51.95	7.11	0.64	Yes	$9.02\cdot10^{-5}$
4	39.58	50.95	9.48	0.64	Yes	$6.9\cdot10^{-2}$
5	38.05	50.11	11.84	0.66	Yes	0.47
6	33.44	48.81	17.75	0.76	Yes	3.21
7	28.64	47.75	23.61	0.96	Yes	7.06
8	41.35	56.29	2.37	0.67	No	0
9	41.70	53.56	4.74	0.64	No	0
10	40.94	51.95	7.11	0.63	No	0
11	39.58	50.95	9.48	0.64	No	0
12	38.05	50.11	11.84	0.66	Yes	$13.32\cdot10^{-4}$
13	33.44	48.81	17.75	0.77	Yes	0.64
14	28.64	47.75	23.61	0.94	Yes	3.23

The voltage variations were checked for different operating conditions, and the voltage levels in the nodes were found to be within the established limits (i.e., deviations do not exceed ±0.1 p.u. threshold). As an example, a color map visualization with the voltage levels is shown in Fig. 4 (a capture during the running scenario 7).

The "colder" colors correspond to lower bus voltage levels (i.e., below 1.0 p.u.), and the "warmer" colors – to higher bus voltage levels (i.e., above 1.0 p.u.).

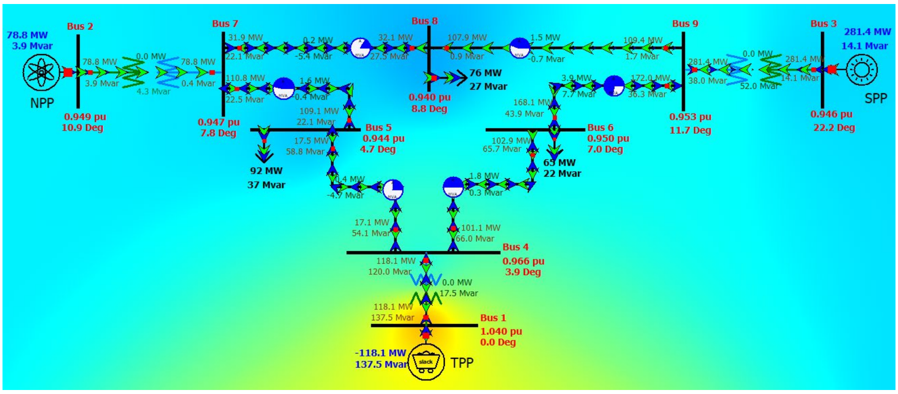

Figure 4

Voltage color map for the UES in PowerWorld (scenario 7)

Dependences of the share of thermal and nuclear power units in the energy generation balance of the UES from PV penetration are shown in Fig. 5. For the scenarios with mild ramp rate of the NPPs (i.e., baseload operation) the shares of TPPs and NPPs in energy generation mix both decrease with the increase of the PV penetration. For the scenarios with additional flexibility of NPPs the share of the NPPs in energy generation mix constantly decreases, while the share of the TPPs moderately increases until the PV penetration level of 50%. Further the share of the TPPs starts to decrease, but its declining proceeds notably slower than the declining of the NPPs.

Comparing flexible and inflexible operation of the nuclear, the share of NPPs in the total generation mix is higher with the NPPs' ramp rate of 20% than with the NPPs' ramp rate of 2% until the PV penetration reaches 30%. At the same time, the share of TPPs in the total energy generation mix is lower with the NPPs' ramp rate of 20% than with the NPP's ramp rate of 2% until the PV penetration reaches 30%. This means that flexible operation of nuclear units allows to better engage them in the demand-supply balancing and to reduce the share of environmentally unfriendly thermal power units. However, when the PV penetration exceeds 30%, the situation changes to the opposite. This can be explained by the peculiarities of NPP regulation under high penetration of RESs. Thus, higher PV penetrations, reduce the value of nuclear flexibility and enhance demand for reserves. Forecasting of solar generation and scheduling of NPPs with regard to the expected SPPs output can be a helpful measure to increase the share of cleaner energy technologies.

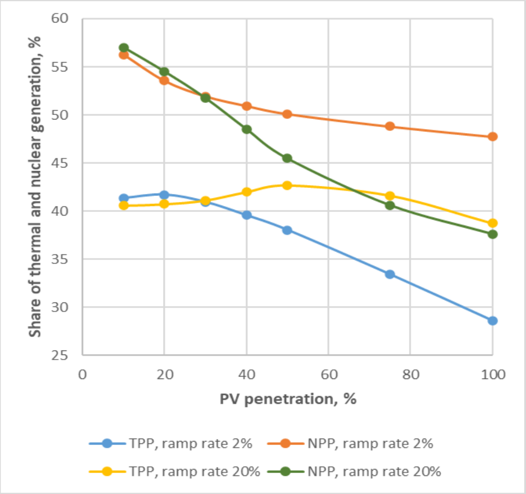

Figure 5
Dependences of the share of TPPs and NPPs in total energy generation

Comparison of power losses in the energy system with different ramp rates of the NPPs is shown in Fig. 6. As it can be seen, additional flexibility of the NPPs has negligible influence on the power losses.

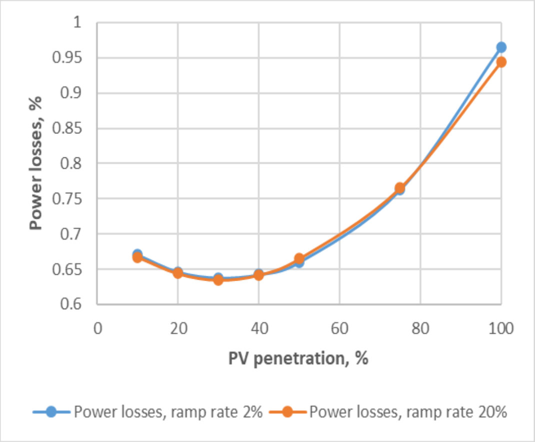

Figure 6
Comparison of power losses in the energy system with different ramp rates of the NPP

Additionally, nuclear flexibility allows to significantly reduce PV curtailment in the system. For example, at high PV penetrations of 75% and 100% (scenarios 13 and 14) the PV curtailment with flexible nuclear power is 0.64% and 3.23% accordingly, while 3.21% and 7.06% of PV generation must be curtailed when there are inflexible nuclear power units in the energy system (scenarios 6 and 7).

Conclusions

Many countries and regions have policy targets in place, which steer the energy system towards meeting future demands for clean, reliable and affordable energy services, using PV and wind technologies. However, high penetration levels of PV in the united energy systems can violate demand-supply balance, cause issues with frequency control and complicate demand-supply management. While TPPs have the best maneuverable generating capacities, NPPs can also contribute to the demand and supply balancing in the UES.

In this paper the potential impacts of flexible nuclear operations within an energy system with a significant share of NPPs, high solar penetration and a strong transmission system has been investigated. The results have shown that a flexible nuclear operation can substantially reduce curtailment of renewables and, in some cases, reduce the share of environmentally unfriendly thermal energy. Higher than a 30% PV penetration reduces the value of nuclear flexibility and enhances the demand for reserves. Forecasting of solar generation and scheduling of NPPs with regard to the expected SPPs output can be a helpful measure to increase the share of cleaner energy technologies, such as nuclear and renewable energy.

Although the numerical results are case specific, the flexible operation of nuclear power stations is likely to yield similar benefits in power systems with comparable shares of RESs and NPPs.

A rigorous sensitivity analysis, exploring which factors are most crucial for economic benefits of nuclear flexibility, would be a productive avenue for future work.

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