Enhancing Security of the Belarusian Power System in the Context of Nuclear Power Expansion

M.A. Kashin[1,*], N.L. Novikov[2], A.N. Novikov[3]

[1] Belenergosetproject RUE, Minsk, Republic of Belarus
[2] JSC "STC FGC UES," JIHT RAS, NRU "Moscow Power Engineering Institute," Moscow, Russia
[3] STC Energobezopasnost', Moscow, Russia

***Abstract* — The security of the Belarusian power system has been historically affected by both internal and external factors. The commissioning of a nuclear power plant (Belarusian NPP) in the Republic of Belarus in 2021 caused radical transformations in the power system due to the need to ensure reliable power output from the plant. Along with changes currently observed in the topology of internal 330 kV grids, there are also changes in the structure of external intersystem 330 kV tie lines. The Belarusian power system is connected to the UES of Russia via one 750 kV transmission line, which brings about the issue of regulating active power flows between the grids of 330 kV and 750 kV voltage classes. Due to the specific structure of the backbone grid of the Belarusian power system and its external connections, we propose solving the above problem by using the phase-shifting transformer (PST) as a type of a phase-shifter to be installed at the backbone 750/330 kV substation Belorusskaya. The paper presents the results of computational experiments, which confirm the efficiency of this type of the PST in the repair and post-emergency states of the Belarusian power system, and an analysis of technical and economic performance indicators.**

***Index Terms*: power system, nuclear power, phase-shifting transformer, active power losses, active power flows, voltage.**

* Corresponding author.
E-mail: m.kashin@besp.by

http://dx.doi.org/10.38028/esr.2022.04.0007
Received November 16, 2022. Revised November 30, 2022.
Accepted December 13, 2022. Available online January 30, 2023.

I. Introduction

The commissioning of a nuclear power plant in the Republic of Belarus in 2021 caused a radical transformation in the power system, as the installed capacity of the Belarusian nuclear power plant is about 40% of the annual maximum load.

The voltage of backbone grid of the Belarusian power system and tie lines with adjacent power systems is 330–750 kV. At present, along with changes in the internal 330 kV lines, there are also changes in the structure of external 330 kV tie lines. In this regard, maintaining the standard backup capacity in the Belarusian power system poses a question of how to regulate the active power flow between the grids of 330 kV and 750 kV voltage classes.

In connection with the changes in the topology of the 330–750 kV backbone grid as was outlined above, given the limited redundancy capabilities of intersystem tie lines, the Belarusian power grid comes close to the need to build an active-adaptive 330–750 kV grid, allowing real-time grid control using phase shifters (PS).

The paper considers the possibility of regulating active power flows along the 750 kV transmission line Smolensk NPP – Belorusskaya, which connects the Belarusian power system and the UES of Russia.

As is known, the active power flow in an AC power line is determined by expression (1):

$$P = \frac{U_1 \cdot U_2}{X_l} \cdot \sin \delta_{21}, \tag{1}$$

where U_1 and U_2 are the voltage magnitudes of the power source at the beginning of the line and the voltage of the electric load at the end of the line;
X_l is line reactance;
δ_{21} is the phase angle between the voltage vector of the power source and the load.

The voltage magnitudes at the power source and load buses (including those at different points of power systems) are obtained based on specified parameters of power flows, equipment reliability, reactive power balances, and other basic conditions, and they do not have a significant regulation range to address the issue of active power flow control. Thus, it follows that the amount of active power transmitted through the transmission line can be controlled in two ways:

- by changing the line reactance,
- by changing the phase angle between the source and load voltage vectors.

The AC line resistance is predominantly inductive in nature. Therefore, one of the engineering solutions to regulate the active power flow along a transmission line is series compensators, which are capacitor batteries connected in series in the transmission line to compensate for part of its inductance. However, in the repair and emergency states of the Belarusian power system, as will be shown below, it is necessary to limit the active power flow along the 750 kV transmission line Smolensk NPP - Belorusskaya.

Therefore, regulating the power flow in the 750/330 kV grid by changing the phase angle between the vectors of voltages at the transmission line beginning and end proves relevant for the Belarusian power system

To regulate the active power flows in three-phase AC grids, one uses the phase shifter, a specialized modification of the power transformer. The phase shifter consists of two transformers: a regulated transformer, which is connected in parallel with the line, and a series transformer, the secondary winding of which is connected in series with the line. In this case, due to the winding connection scheme, the voltage vector on the series winding is directed at an angle of 90 electrical degrees to the phase voltage of the grid.

By changing the voltage on the series winding with a regulated transformer, it is possible to rotate the vector of total voltage at the beginning of the grid and control the shift angle between the voltage vectors at the beginning and at the end of the transmission line by changing the active power flow transmitted through it relative to the natural load flow [1].

There are two types of phase shifters:

- phase-shifting transformers (PST): they can continuously regulate quadrature voltage;
- quadrature booster: they regulate step voltages.

The quadrature booster (QB) is a single-tank three-phase transformer with no tap changers. QB is a simple, cheap, and reliable phase shifter used in power flow control in a 220–500 kV grids of elaborate topologies.

At 750 kV substations (SS), the functions of the PST can be performed by a quadrature booster installed at the neutral point of a 750/330 kV autotransformer (AT).

It is worth noting that at present, the output voltage phase shift is changed mainly by means of traditional mechanical on-load tap changers (OLTC). OLTCs have a relatively low response time (a few seconds) and a relatively low reliability. However, if it is necessary to increase the speed of the phase shifter, thyristor switches can be used, which perform a similar function of switching transformer windings using thyristors or triacs [1].

Phase shifters have been widely used globally since the second half of the 20th century. Phase shifters have been used in the British power grid since 1969 [2]. In the IPS of the North-West at the Leningrad NPP, 750/330 kV AT1 is equipped with a phase shifter. In 2019, a 500/220 kV phase shifter with a capacity of 195 MVA was commissioned at the Volzhskaya HPP [3]. Since 2009, the 500 kV Ulken substation in Kazakhstan has been using a 500/220 kV phase shifter with a capacity of 400 MWA [4].

II. Special Considerations Relating to the Application of Phase Shifters in the Belarusian Power System

The Belarusian power system is connected to adjacent power systems through the 750 kV power line Smolensk NPP – Belorusskaya and some 330 kV transmission lines, whose load is formed on the basis of power flows of all power systems involved. The lack of control of the distribution of active power between transmission lines of 330 kV and 750 kV voltage classes limits the utilization of the design capacity of grid elements. These limits do not allow going through all maintenance and emergency states without changing the structure of generating and consuming facilities in the Belarusian power system, which compromises the security of the power system.

The substation that serves as a junction connecting 750 kV and 330 kV grids is the 750 kV Belorusskaya substation. A unique feature of the 750 kV Belorusskaya substation circuit is that the 750 kV and 330 kV grids are connected through a single component being the 750/330 kV AT.

The analysis of the experience of operating PSTs in CIS countries indicates that the most appropriate way to regulate the power flows through the 750/330 kV AT of the 750 kV Belorusskaya substation is to use a standard single-phase regulating transformer of the ODTsNP 92000/150 type, designed specifically to work with the 750/330 kV AT and already proven in use.

Our study attests to the fact that the use of this engineering solution, both in normal and in emergency states, offers the opportunity to control the loading of the 750/330 kV autotransformer, and, consequently, that of the only 750 kV transmission line Smolensk NPP – Belorusskaya.

Currently, the Belarusian power system is connected to the adjacent power systems of Russia, Lithuania, and Ukraine through eight 330 kV transmission lines and one 750 kV transmission line. The 330 kV power transmission lines previously connected to the Ukrainian power system were disconnected due to Ukraine's joining ENTSO. In the case of the withdrawal of the Lithuanian power system from parallel operation with the Belarusian power system, only four power lines, including three 330 kV transmission

Fig. 1. 330 kV and 750 kV transmission lines connecting the Belarusian power system with the UES of Russia.

lines and one 750 kV tie line with the UES of Russia, will remain in operation (Fig. 1):

1. 750 kV overhead line Smolenskaya NPP – Belorusskaya;
2. 330 kV overhead line Krychaw – Roslavl;
3. 330 kV overhead line Viciebsk – Talashkino;
4. 330 kV overhead line Polatsk – Novosokolniki.

III. Calculations of Power Flows and Voltages

The expansion of power grids is accompanied by an increase in additional power and electricity losses caused by the growth of equalizing power due to their heterogeneity. In this case, grids of different voltage classes are loaded according to their impedances and topology, and the transfer capability of the entire closed network is often limited by its single component. Managing the power flow of such a network can optimize active power and electricity losses and ensure the required level of transfer capability of such a closed network by redistributing power flows between grids of different nominal voltages.

As noted above, the standard solution for regulating the flows between the 330 kV and 750 kV grids is to install a phase-shifting transformer (PST) with a regulation range of ± 68 kV (± 20 × 5%) in the primary winding of the existing 750/330 kV AT, which performs **quadrature control** of the AT voltage.

To perform **in-phase voltage control**, an on-load tap changer (OLTC) with a ± 64 kV (± 20 × 5%) additional EMF regulation range is currently installed at the neutral point of the AT of the 750 kV substation Belorusskaya.

The additional EMF of the phase-shifting transformer is directed at a 90º angle to the main phase voltage. The in-phase and quadrature voltage control is carried out at the neutral point of the 750/330 kV autotransformer. Therefore, the total transformation ratio of the autotransformer is a complex number and is defined by the expression:

$$K_{Ò} = \frac{\frac{U_{nom.MV} \pm \text{Ä}U_{OLTC}}{\sqrt{3}} + j\text{Ä}U_{PST}}{\frac{U_{nom.HV} \pm \text{Ä}U_{OLTC}}{\sqrt{3}} + j\text{Ä}U_{PST}} = K_{ÒR} + jK_{ÒI}, \quad (2)$$

where

$U_{nom.MV}$ – nominal voltage of the MV winding of the autotransformer, equal to 330 kV;

$U_{nom.HV}$ – nominal voltage of the HV winding of the autotransformer, equal to 750 kV;

ΔU_{OLTC} – the value of additional in-phase EMF generated

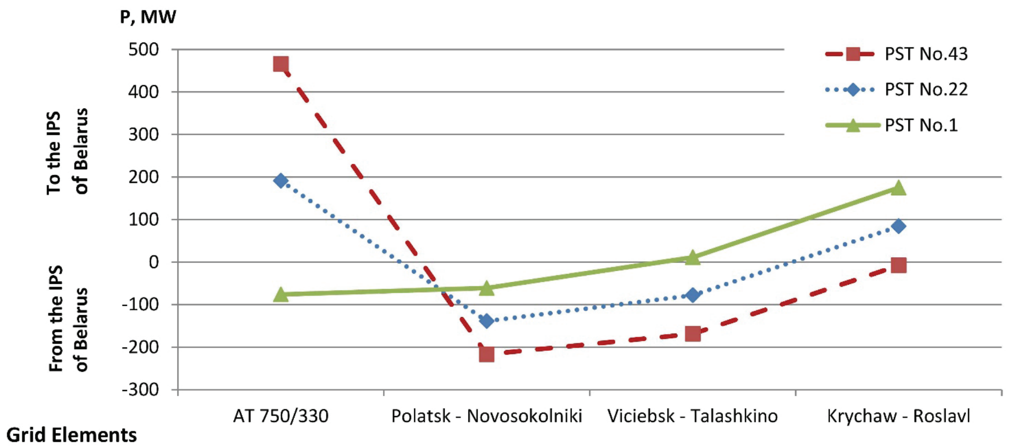

Fig. 2. Profile of active power flows on 330 kV transmission lines and the 750/330 kV AT of the IPS of Belarus with different PST taps selected in the normal operating state.

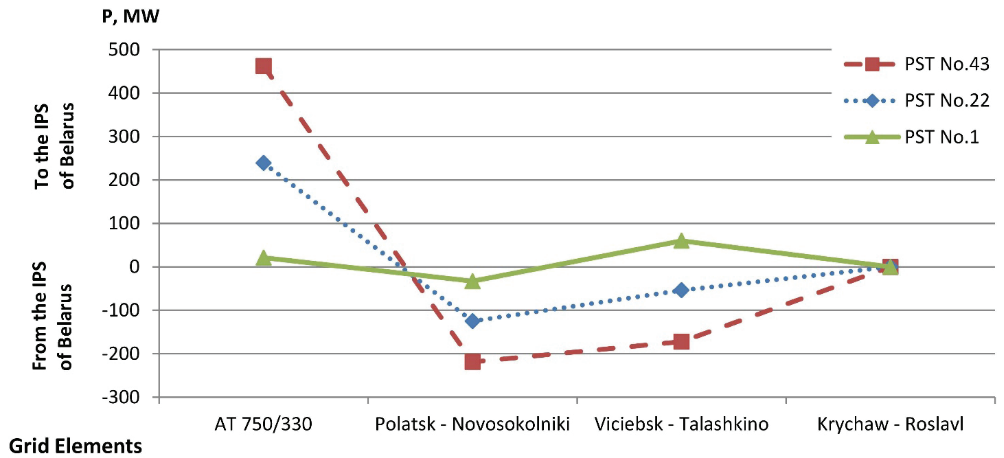

Fig. 3. Active power flow profiles along the 330 kV transmission line and the 750/330 kV AT of the IPS of Belarus with different PST taps selected in the maintenance state (disconnection of the 330 kV Krychaw – Roslavl overhead line).

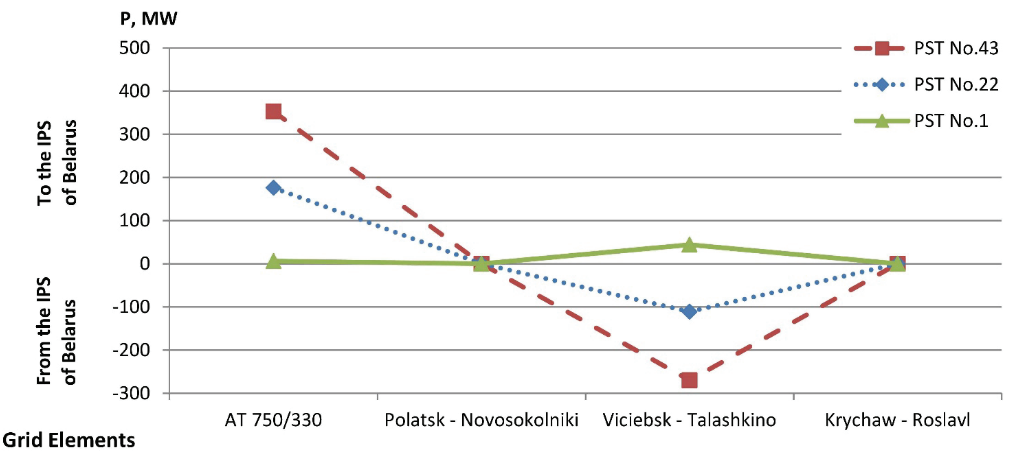

Fig. 4. Active power flow profiles along the 330 kV transmission line and the 750/330 kV AT of the IPS of Belarus with different PST taps selected in the maintenance and emergency state (disconnection of 330 kV overhead lines Krychaw – Roslavl and Polatsk – Novosokolniki).

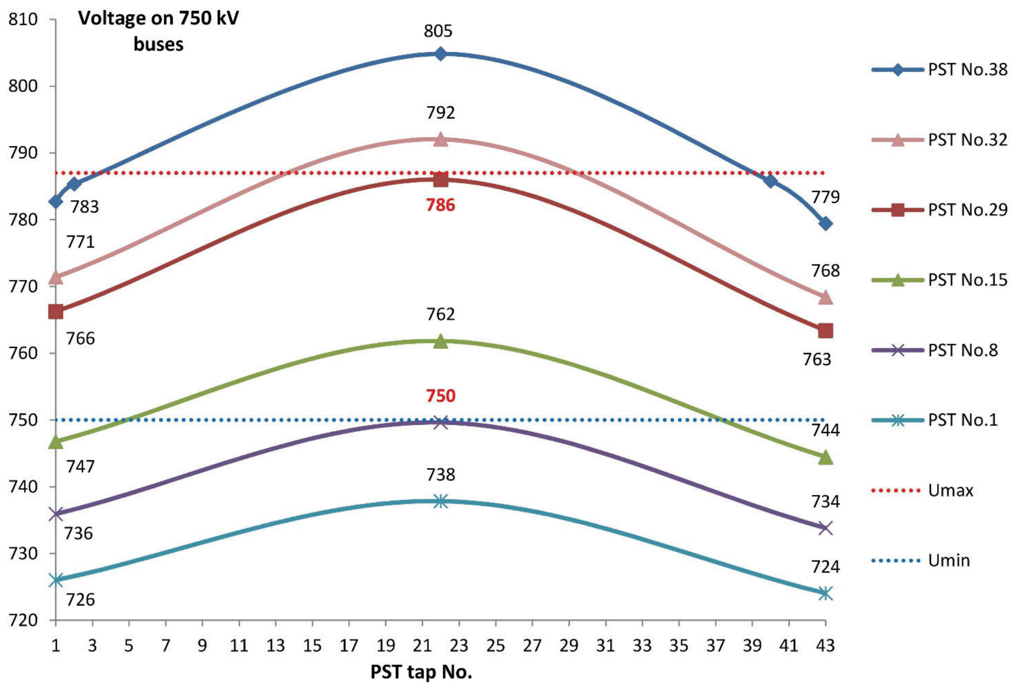

Fig. 5. Alignment chart of voltage on 750 kV buses of the 750 kV substation Belorusskaya for different positions of taps of the OLTC and PST.

by the OLTC (± 64 kV);
ΔU_{PST} – the value of the additional quadrature EMF generated by the PST (± 68 kV).
K_{TR} – the real part of the complex transformation ratio;
K_{TI} – the imaginary part of the complex transformation ratio.

The technical performance of the PST at the 750 kV substation Belorusskaya was evaluated through a series of electrical analysis calculations of the backbone grid of the IPS of Belarus in its normal and maintenance states under different PST taps (there is no quadrature control in the case when PST tap No. 22 is selected) for winter maximum and summer minimum power flows. In the calculations of power flows, we assumed that the condition of the self-balancing of the Belarusian power system holds in terms of active power.

Analysis of the calculation results shows that the regulation ranges of active power flows between the 330 kV and 750 kV grids are determined by the grid configuration and do not depend on the level of loads. The configuration of the grid of the Belarusian power system does not depend on the season of the year, therefore, below are the results of calculations for winter maximum power flows.

The profiles of active power flows over the 750/330 kV AT and 330 kV transmission lines (Krychaw – Roslavl, Viciebsk – Talashkino, and Polatsk – Novosokolniki) with different PST taps selected in the normal, maintenance (n – 1), and maintenance-emergency (n – 2) states are shown in Fig. 2–4.

The analysis of Figures 2–4 shows that the possible range of change in the active power flow through the 750/330 kV AT of the 750 kV substation Belorusskaya is as follows:

- in the normal operating state, it is 540 MW,
- in the repair state – 440 MW;
- in the maintenance and emergency state – 350 MW.

Consequently, with the in-phase and quadrature voltage control at the 750 kV substation Belorusskaya, the flow of active power can be transmitted from the 330 kV grid of the cross-border section of the IPS of Belarus – IPS of the Center to the 750 kV overhead line Smolenskaya NPP – Belorusskaya and back, in the range of 540-350 MW.

The security of the power system is understood as the ability to withstand sudden power flow changes, preventing cascading accidents with mass disruption of power supply to consumers. The deterministic criterion n – 1 is widely used to assess the security of a power grid. The criterion means that in case of emergency involving the loss of any independent component of the grid, the grid continues to perform its functions in full [5].

One of the objectives of this study was to ensure the security of the power system by providing the required transfer capability of 750 kV and 330 kV tie lines in the event of an emergency shutdown of the Belarusian NPP.

The power flow analysis performed for a shortage of active power in the Belarusian power system (in case of an emergency shutdown of the Belarusian NPP) shows that the limiting element for receiving backup power is the 750/330 kV AT at the 750 kV substation Belorusskaya, whereas the transfer capability of the 330 kV transmission lines proved adequate. In these states, the PST allows eliminating the overloading of the 750/330 kV AT by increasing the load of 330 kV transmission lines by about 200–250 MW. Thus, when receiving backup power from the UES of Russia, there is no overloading of grid elements and no need to disconnect consumers.

Managing the loading of 750 kV and 330 kV grid elements using the PST also makes it possible to go through maintenance states in the backbone grid of the Belarusian power system without compromising the required parameters.

IV. Additional Considerations Related to the Use of the PST

As mentioned above, during an emergency shutdown of the Belarusian NPP, the PST allows increasing the transfer capability of tie lines of the Belarusian power system by up to 250 MW, and, consequently, the power system does not incur losses for electricity not served. The economic effect from the installation of the PST, according to aggregate estimates, will be 110% of the cost of its installation.

In addition, a similar effect of eliminating the imbalance of active power in the power system can be achieved by constructing a new 330 kV overhead tie line or a shunting generating unit of similar capacity. The cost of PST installation is 10–20 times less than the cost of either of the above options.

It should be noted that the possibility of regulating active power flows between the 750 kV and 330 kV grid is determined by the permissible voltages for these grids (787 kV and 363 kV, respectively). Voltages at the nodes of the 330–750 kV power system are determined by reactive power balances, which largely depend on the active power load of consumers and, consequently, the load with respect to the active power of grid elements.

Figure 5 shows an example of an alignment chart of the voltage on the buses of 750 kV substation Belorusskaya for different positions of taps of the on-load tap changer and PST.

Since the change in the power system load is a dynamic process with not infrequently sharp fluctuations in active power (in case of emergencies), in the future, the real-time determination of the tap of the PST and OLTC appropriate for the current state (with the aid of an alignment chart similar to Fig. 5) will require the creation of a digital twin of the in-phase and quadrature control device [2] and its integration into the model of the digital twin of the power system.

V. Conclusion

1. With the PST, the control ranges of active power flows between the 330 kV and 750 kV grid are determined by the grid configuration and do not depend on the magnitude of loads.
2. The use of PST to control loading of 750 kV and 330 kV grid elements makes it possible to go through all maintenance, maintenance-and-emergency, and emergency states without constructing new transmission lines.
3. When adopting the PST, it is advisable to create its digital twin and integrate it into the model of power system digital twin.

References

[1] M. G. Astashev, M. A. Novikov, D. I. Panfilov, “Application of phase shifters with thyristor switches in active-adaptive power grids,” *Energy of Unified Grid*, no. 5, pp. 70–77, 2013. (In Russian)

[2] V. V. Bushuev, N. L. Novikov, A. N. Novikov, “Digitalization of economy and energy: prospects and challenges,” *Economic Strategies Magazine*, no. 6, pp. 96–105, 2019. (In Russian)

[3] A. S. Brilinsky, G. A. Evdokunin, V. A. Kritsky, Yu. V. Matvienkov, A. P. Sidelnikov, L. S. Smirnova, “Phase-shiting transformer in the power supply circuit of a large hydropower plant,” *Proceedings of the STC of the Unified Energy System Moscow*, no. 1 (80), pp. 6–14, 2019. (In Russian)

[4] G. Evdokunin et al, “Phase-shifting transformer put to use in Kazakhstan for the first time in the CIS,” *The News of Electrical Engineering*, no. 6 (48), pp. 12–16, 2008. (In Russian)

[5] M. G. Astashev, M. A. Novikov, D. I. Panfilov, P. A. Rashitov, T. V. Remizevich, M. I. Fedorova, “On power flow analysis of power transmission lines with regulated phase shifters,” *Proceedings of RAS. Power Engineering*, no. 1, pp. 15–23, 2016. (In Russian)

Mikhail A. Kashin graduated from the Belarusian National Technical University, Faculty of Power Engineering, with a bachelor's degree in engineering, in 2000. Currently, he is a lead engineer of the Department of Energy System Design at RUE "Belenergosetproekt." His research interests include the study of adequacy and security of electric power systems, their structure, and dynamics of development.

Nikolai L. Novikov graduated from Novosibirsk Institute of Electrical Engineering (now Novosibirsk State Technical University), Faculty of Electrical Engineering, in 1970. In 2001, he received the D.Eng. degree from Novosibirsk State Technical University. Currently, he is a Deputy Scientific Director of JSC "STC FGC UES," a lead researcher at the JIHT RAS, a professor at the FSBI of HE "NRU MPEI." His scientific interests include control of operating conditions of electric power systems.

Alexander N. Novikov graduated from Novosibirsk State Technical University, Faculty of Power Engineering, in 1996. Currently, he is a senior researcher in the Scientific and Organizational Department of the FBU "STC "Energobezopasnost."His research interests focus on the issues of increasing the reliability and ensuring the safety of electric power systems.