

Article

Comparison of Phase-Shifting Transformers Properties

Paweł Albrechtowicz ^{1,*} , Bartosz Rozegnał ¹  and Piotr Cisek ² ¹ Department of Electrical Engineering, Cracow University of Technology, Warszawska 24 St., 31-155 Cracow, Poland² Department of Energy, Cracow University of Technology, 31-864 Cracow, Poland

* Correspondence: pawel.albrechtowicz@pk.edu.pl

Abstract: This article presents different phase shifting transformers (PSTs) types and their influence on the transmitted active power and energy parameters. Typical PSTs, both symmetrical (SPST) and asymmetrical (APST), are compared to the asymmetrical controllable PST (ACPST). The ACPST allows for regulating both quadrature and longitudinal voltage, which makes this type interesting in practical applications and power flow optimizations. The collected data enable a direct comparison of these PSTs' properties. APST allows high power transfer, but the voltage increase in some cases cannot be acceptable. SPST type in taken tests has the best properties concerning the transferred power, output voltage, and internal voltage drop. ACPST, in its primary mode, can be efficiently used as a substitute for the SPST. However, in some range of injected quadrature voltages, it can achieve even better properties than the SPST. The laboratory and simulation tests allow the development of the ACPST regulation to achieve the best properties among other PSTs, with the possibility to operate, e.g., on the constant ACPST output voltage, in quasi-symmetrical mode and any other, which may be needed in power systems.

Keywords: phase-shifting transformers; power flows; phase angle



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1. Introduction

The constant development of power systems requires new solutions in many fields involved in the safe and reliable process of electrical energy delivery. For better power flow control, phase shifting transformers (PSTs) are used among different devices enabling their regulation. These devices allow one to achieve voltage phase angle regulation and influence the transmitted power, both to increase or reduce the actual value of the flowing power. In Europe, the PSTs have been widely used in the Benelux region [1,2], in central parts (Germany–Poland, Germany–Czech Republic) [3], or in the south (Italy–Slovenia) [4]. These examples show that they can be efficiently used to control power flows; therefore, the next PST units are planned to be installed or are already under construction. These development plans are available in references [5,6], which are elaborated on and published by the European Network of Transmission System Operators for Electricity (ENTSO-E).

PSTs are widely used as a power flow control tool. They can be used as a device to avoid loop flows, which are a severe problem, e.g., in the cross-border transmission lines on the following route: Germany → Poland → the Czech Republic → Germany [7–9]. In [7], transmission system operators (TSOs) from Poland, the Czech Republic, Slovakia, and Hungary point out that the critical factor for the unplanned flows in middle-eastern Europe is the power transfer between Germany and Austria. The more planned power flows to Austria, the more loop flows occur from north Germany to Poland and the other countries mentioned. The high risk of transmission line congestion in the Polish national power system is analyzed in [8] due to unplanned flows. The authors in reference [9] clearly show that PST can be a handy tool to eliminate loop flows.

PSTs are considered in some literature during optimization of the grid development planning process or the PST installation place. In [10], the authors propose a parti-

cle swarm optimization (PSO) algorithm to obtain PST's settings in unplanned power flow minimization.

Besides classical PST, the literature proposed the Sen transformer as an effective device for power flow regulation [11] and its expanded versions [12,13] called the extended Sen transformer.

A very popular research subject concerns protective devices for PSTs [14,15]. In [14], a PST electromagnetic model is presented to conduct protection device tests during transient states. In [15], the authors consider hexagonal PST and the protective apparatus for safe and reliable work.

According to the constant development of the power systems, it seems appropriate to consider PSTs not only as the devices installed in the extra high voltage (EHV) and high voltage (HV) systems but also in lower-voltage levels. This assumption results from increased renewable energy sources and their remote location and connection to the power system. Therefore, the authors present a comparative analysis of well-known PST solutions and their own unique construction.

The fundamental PSTs division is in the symmetrical phase-shifting transformer (SPST) and asymmetrical phase-shifting transformer (APST). Their principles are described in reference [1]. However, besides the principles of their work, there is insufficient data about their comparison in relation to their work and influence on the parameters of the transmitted energy. First, many scientific publications refer to their installation in any testing power system consisting of a few, several dozen, or even more than one hundred buses. Their work researches the influence on the whole system, with the proper realization of one objective function such as maximal power flow and minimization of power loss. Therefore, in this article, the main goal is to analyze the operational properties of the SPST, APST, and the authors' construction of the in-phase PST, called the asymmetrical controllable phase shifting transformer (ACPST).

This article's results are obtained for the single cross-border transmission line connecting two systems with installed PSTs. The comparative analysis is prepared to show each PST type's advantages and disadvantages in a typically considered power system scheme scenario representing the influence of angle regulation. The base point of this research is stated on the laboratory transformer unit data. The laboratory tests were conducted for the ACPST type for nominal line-to-line voltage. Then, those results were compared to the simulation equivalent, and as the next step, Simulink models with APST and SPST units were created. Due to the convergence of the laboratory and simulation models, it was found that, in this case, the simpler models (APST, SPST) will also converge. For this reason, the results of simulation calculations for various types of phase-shifting transformers were compared. Additionally, for all PSTs, real values of the winding resistance and reactance for each added series voltage were taken into account.

In the analysis, both for measurements and simulations, the authors considered the active power transmission, the output PST's voltage, the additional introduced voltage phase angle, and the real voltage injected into the line as the most important parameters of each PST type during its operation in the power systems.

Based on the literature review, the reader can note a gap in the research regarding the comparison of each PST type concerning their electrical properties and their influence on the power flow in the classically considered arrangement.

2. Phase-Shifting Transformer Types

The most common PST division in the literature is known as asymmetrical and symmetrical.

Each type can also be prepared as in-phase units, able to control both longitudinal and injected quadrature voltage. With the proper connection of phases energizing the series windings, it is possible to inject voltages with different phases, such as $\pm 120^\circ$, $\pm 60^\circ$, and $\pm 90^\circ$. In this paper, only quadrature voltage implementation is considered.

The general formula for the active power flow is given by Equation (1):

$$P = \frac{U_L U_R}{X} \sin(\delta + \alpha) \quad (1)$$

where U_L is the PST output voltage, U_R is the end line voltage, X is the longitudinal reactance, δ is the nominal phase angle between both lines' ends, and α is the additional phase angle implemented by the PST.

The PST type defines the possible angle α , and the mathematical formulas on this angle are presented below:

$$\alpha_{APST} = \arctg\left(\frac{\Delta U}{U_S}\right) \quad (2)$$

$$\alpha_{SPST} = 2\arcsin\frac{|\Delta U|}{2|U_L|} \quad (3)$$

where ΔU is the injected series voltage, V, and U_S is the PST input voltage, V.

Equation (2) describes angle α in the case of the APST, and Equation (3) describes the SPST dependency. Using these equations, active power flow is given according to Equations (4) and (5) for APST and SPST, respectively.

$$P = \frac{U_R}{X} (U_S \sin \delta + \Delta U \cos \delta) \quad (4)$$

$$P = \frac{U_R U_L}{X} \sin\left(\delta + 2\arcsin\frac{|\Delta U|}{2|U_L|}\right) \quad (5)$$

Based on those formulas, the characteristics can be obtained (Figures 1 and 2).

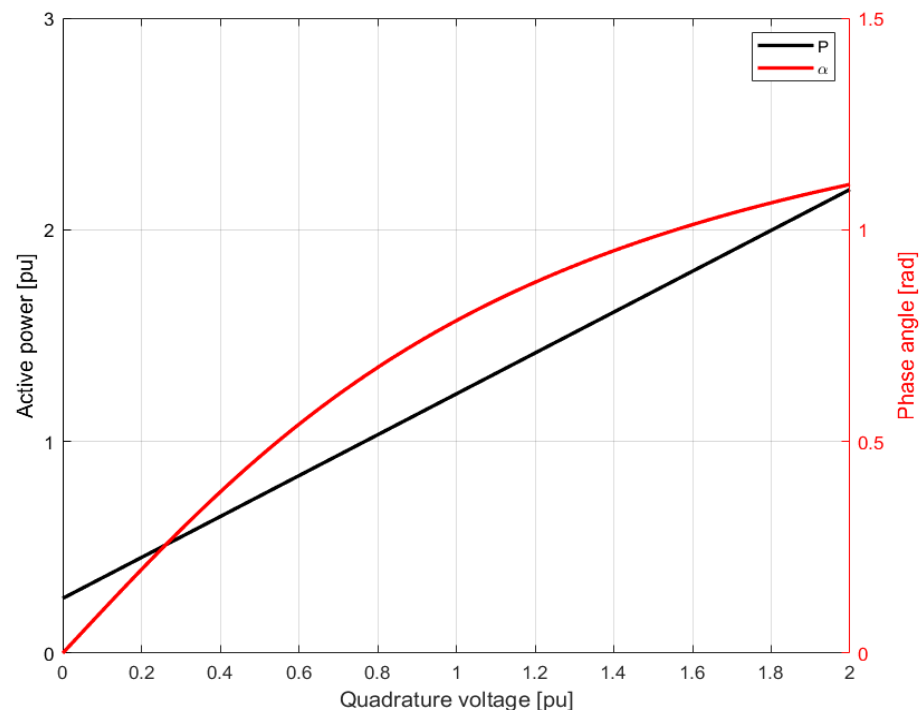


Figure 1. APST active power flow and angle versus injected quadrature voltage.

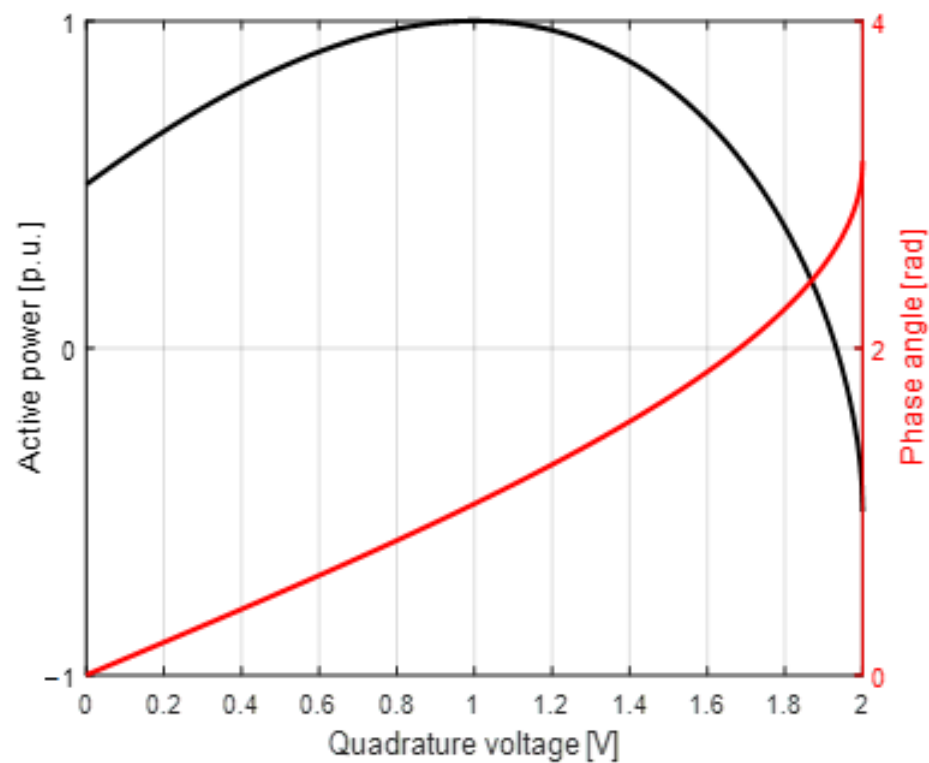


Figure 2. SPST active power flow and angle versus injected quadrature voltage.

3. In-Phase Asymmetrical PST

In references [16,17], the in-phase PST is described, also called the asymmetrical controllable phase-shifting transformer (ACPST). This name is the consequence of the possible regulation range of the ACPST. In this PST unit, the longitudinal and quadrature voltage can be controlled independently, which allows for better power flow control possibilities. The simplified connection scheme of the ACPST is presented in Figure 5. A mathematical description of the ACPST is given by Equations (6) and (7).

$$\alpha_{ACPST} = \arctg\left(\frac{\Delta U \theta}{U_S}\right) \quad (6)$$

$$P = \frac{U_R}{X} \left(\frac{U'_S}{\theta} \sin \delta + \Delta U \cos \delta \right) \quad (7)$$

where U'_S is the voltage after longitudinal transformation, V (Figure 5).

Comparing Equations (6) and (7) with (2) and (4), it is clear that ACPST is described similarly to APST. The difference between them is in the θ , which appears in ACPST formulas and is described as the extra transformer ratio ($\theta = U_{Sx}/U'_{Sx}$). This value regulates the longitudinal voltage in the case of ACPST. For $\theta = 1$, ACPST will work as APST.

Figure 3 presents the active power flow versus injected quadrature voltage. When the longitudinal voltage is higher than the nominal (105% U_n —red case), the total active power transfer is also higher by approximately 5%, which directly results from Equation (7). The angle α range is presented in Figure 4.

Without a doubt, comparing all PST types, one can see that ACPST provides the best regulation flexibility. This unique feature resulting from the construction may lead to these units' use in power systems with high penetration of renewable energy sources. In these systems, the voltage variability is often very high, so a control device such as PST adjustment is required.

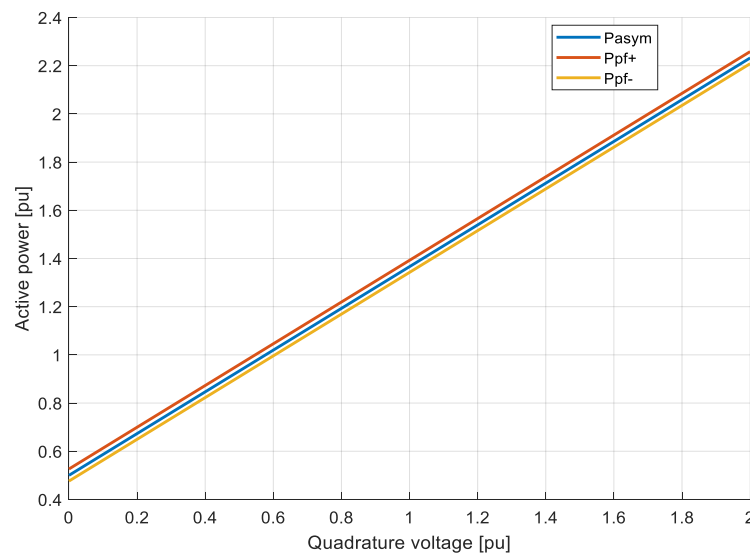


Figure 3. ACPST active power flow for 95% Un (yellow), Un (blue), and 105% Un (red).

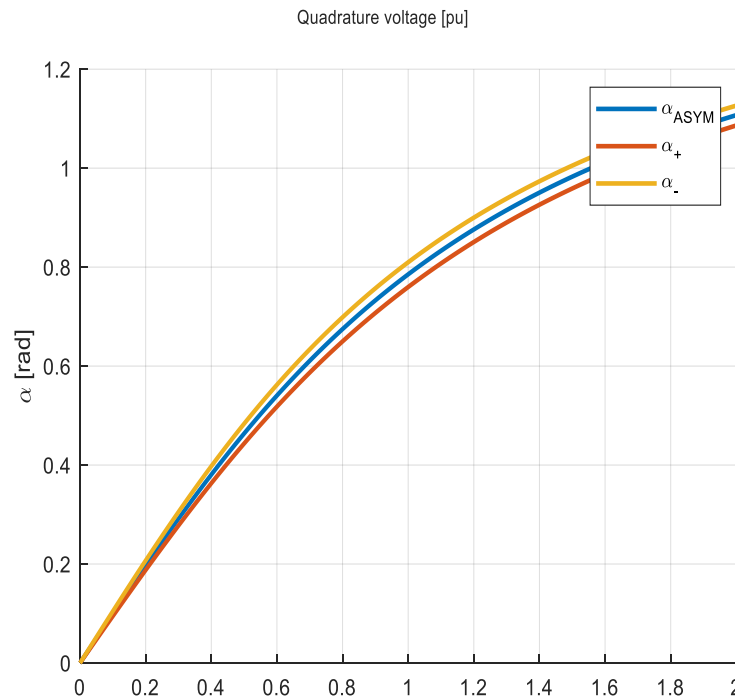


Figure 4. ACPST angle α range for 95% Un (yellow), Un (blue), and 105% Un (red).

4. Laboratory Arrangement and Simulations

Laboratory tests were performed on the two transformer ACPST constructions with the parameters presented in Table 1. Figure 5 presents a single-phase laboratory ACPST scheme. Both the series transformer (ST), responsible for injection of the quadrature voltage into the line, and the extra transformer (ET), able to control the longitudinal voltage, can be connected to a star (Y) or delta (D). Depending on the mutual connection of ST and ET, series voltages with angles of $\pm 90^\circ$, $\pm 60^\circ$, and $\pm 120^\circ$ can be obtained. In this article, only $\pm 90^\circ$ cases were analyzed.

Table 1. Transformers' data.

	Series Transformer ST	Extra Transformer ET
Rated Primary Voltage [V]	3×400	3×400
Rated Secondary voltage [V]	$3 \times 128/3 \times 64/3 \times 32/3 \times 16/3 \times 8/3 \times 4$	$3 \times 400 + 5 \times 1.5\% - 10 \times 1.5\%$
Rated Primary Current [A]	3×33.2	3×33
Rated Secondary Current [A]	$3 \times 30/3 \times 30/3 \times 30/3 \times 30/3 \times 30/3 \times 30$	3×32.5
Rated Power [kVA]	22.5	22.5
Rated Frequency [Hz]	50	50
Connection Group	D/iiiiii *	Yy0
Short-Circuit Voltage [%]	3.88	5.10

*—the insulated windings connected in series to the transmission line.

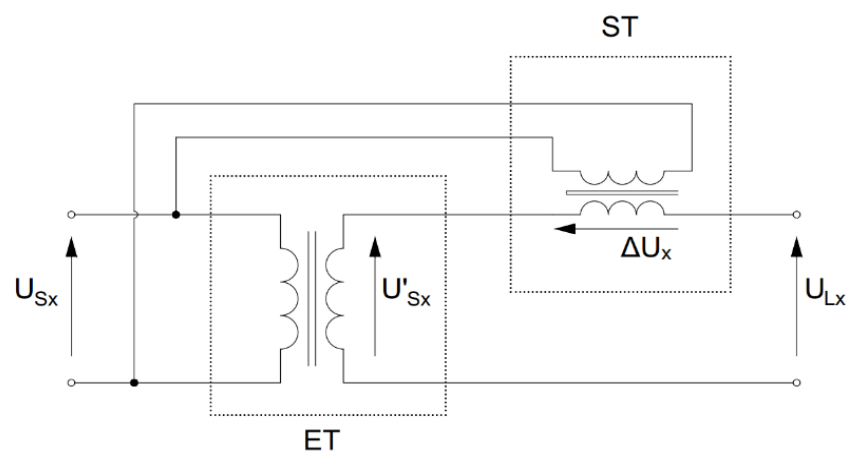


Figure 5. The ACPST single-phase equivalent scheme. ET—extra transformer responsible for longitudinal voltage regulation, ST—series transformer implementing quadrature voltage into the line, U_{Sx} —input voltage of any phase, U'_{Sx} —regulated longitudinal voltage of any phase, ΔU_x —quadrature voltage injected into the line, U_{Lx} —PST output voltage of any phase.

The regulation and possible angles and output voltage values for the laboratory ACPST are shown in Figure 6.

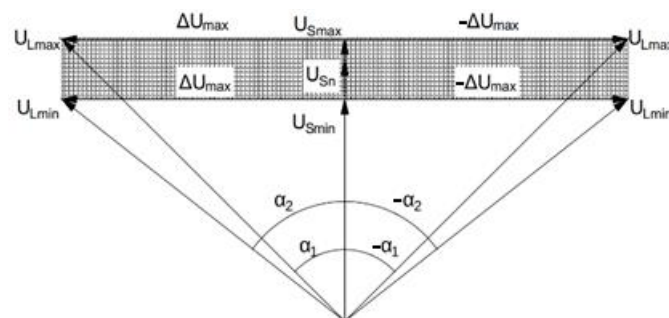


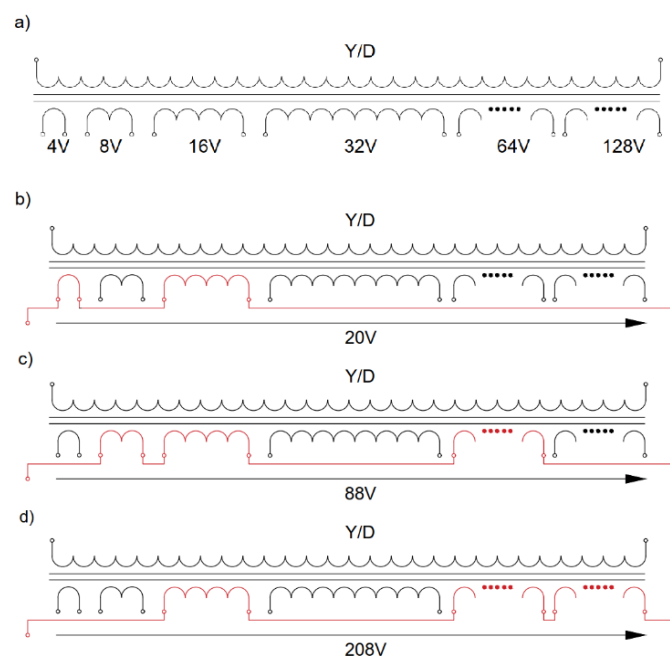
Figure 6. The laboratory ACPST phasor diagram for all control possibilities.

The ACPST can be used as a normal transformer with only longitudinal voltage regulation ($\Delta U = 0$). For the chosen values of the ACPST, the output parameters are presented in Table 2.

Table 2. Parameters of the output voltage and phase angle for chosen cases of ACPST settings.

Longitudinal Voltage U_S	Quadrature Voltage ΔU	Output Voltage U_L [V]	Angle α [°]
U_{Smax}	0	248	0
U_{Smin}	0	196	0
U_{Smax}	ΔU_{max}	356	± 45.9
U_{Smin}	ΔU_{max}	322	± 52.6
U_N	ΔU_{max}	344	± 48.1

The resented values are the maximum. Due to this, some of these cases cannot be implemented into the low-voltage system with a nominal voltage of 230 V (phase to ground and within range $\pm 10\%$). Because of the series transformer's secondary winding construction, these values are presented as impossible to obtain. The ST secondary side has six windings with values presented in Table 1. When all windings are connected (in series), the quadrature voltage injected into the line equals 252 V (ΔU_{max}). Figure 7 presents some cases of the ST secondary windings connections.

**Figure 7.** Some possible connections of the ST secondary windings in a single-phase equivalent: (a) The base set, (b) 20 V quadrature voltage, (c) 88 V quadrature voltage, (d) 208 V quadrature voltage.

The laboratory testing system, besides ACPST units, consisted of supply systems with nominal parameters:

- System S: $Z_S = 0.31 + j0.34 \, \Omega$, $U_S = 420 \, V$.
- System R: $Z_R = 1.05 + j0.66 \, \Omega$, $U_R = 395 \, V$.

Both systems were connected via a transmission line prepared as a distribution line of π -type with the following unitary parameters: $RL1 = 0.04 \, \Omega$, $XL1 = 0.23 \, \Omega$, $BL1 = 2.5 \, \mu S$ [18]. The system's single-phase equivalent scheme is shown in Figure 8.

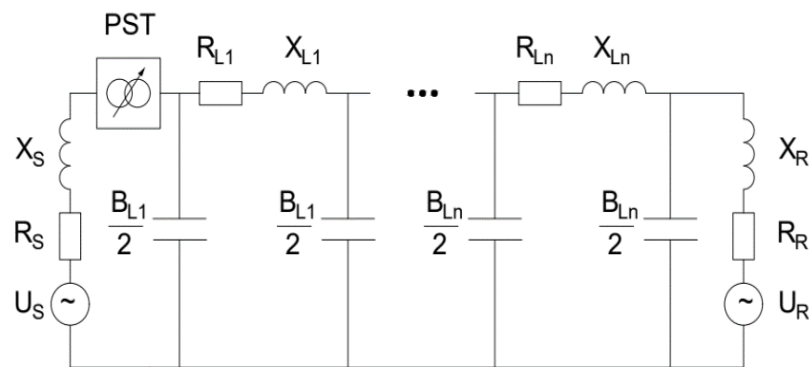


Figure 8. Simplified laboratory testing scheme.

Simulation models were prepared based on the laboratory transformer units and other elements' parameters. The results of the ACPST laboratory and simulation model are compared to validate the basic model. Then, this model was used to simulate APST and SPST cases. The obtained results were compared and analyzed in terms of the electrical parameters of the PST and transferred power.

In Figure 9, the PST's basic simulation set in Simulink is shown. Depending on the considered type, a different PST connection was implemented in the subsystem called "ACPST/APST/SPST".

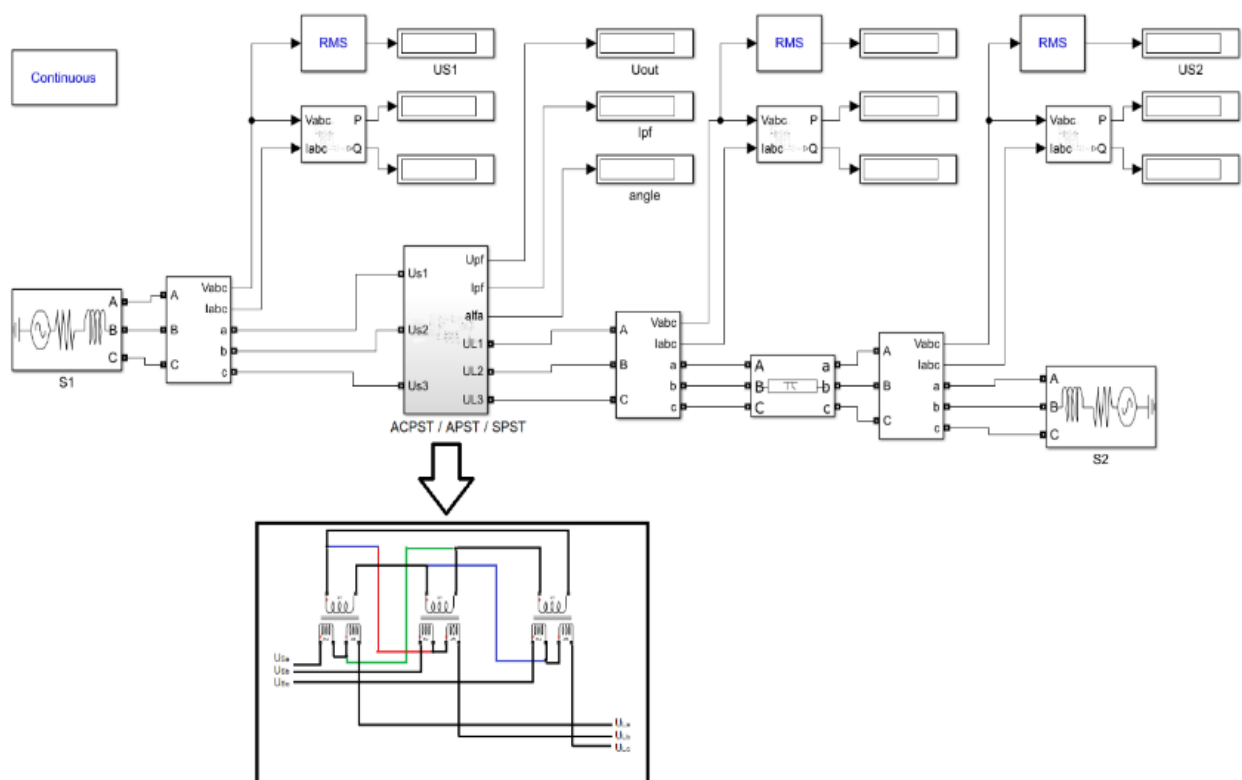


Figure 9. The Simulink connection scheme for simulation tests of ACPST, APST, and SPST cases.

5. Research Results

5.1. Laboratory Measurement and Model Validation for ACPST Case

The laboratory tests were performed for the cases of longitudinal voltage U_S equal to 196 V and 230 V (line-to-line voltage 340 V and 400 V, respectively). The line length was set as 22 sections. The comparison of the obtained active power flows for 196 V and 230 V longitudinal voltage during laboratory measurements is presented in Figure 10.

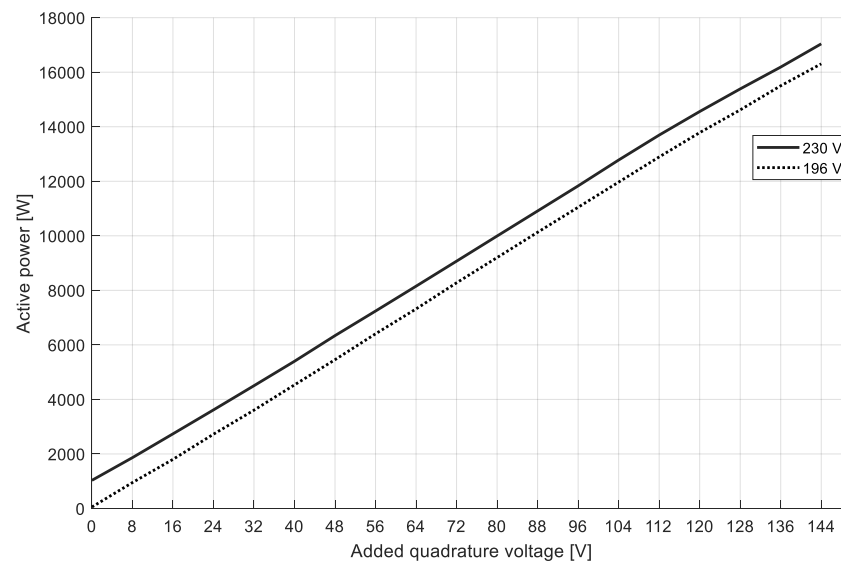


Figure 10. Measured active power flows versus injected quadrature voltage for analyzed two cases of longitudinal voltages.

Comparing both cases in Figure 10, one can note that the same active power flow is possible by adding an 8 V higher quadrature voltage in the case of the 196 V longitudinal voltage. This way, one can obtain the same active power flows with lower PST output voltage values. The confirmation of this dependency is shown in Figure 11. The output voltage comparison clearly shows the advantage of the ACPST's lowered longitudinal voltage case above the nominal one. First, the line voltage can be efficiently controlled to avoid its increase above the voltage line limits. The lowered voltage does not result in a significant active power flow decrement. As presented in Figure 10, the total transferred active power line for both cases was approximately 8 V higher in quadrature voltage for the 196 V case.

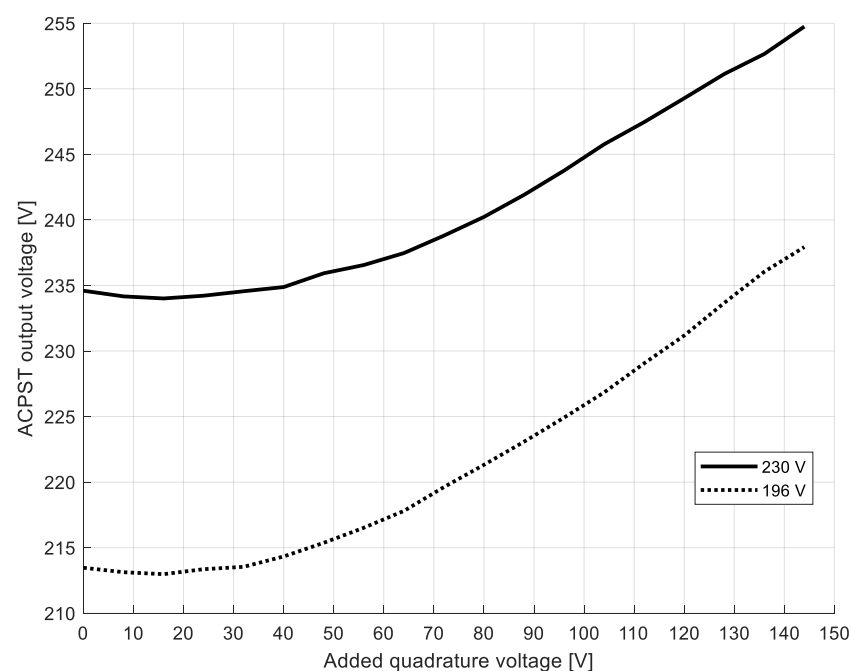


Figure 11. ACPST output voltage versus added quadrature voltage for two cases of longitudinal voltages (230 V—continuous line, 196 V—dotted line).

The actual laboratory unit is compared to the simulation model. Figure 12 presents both analyzed cases obtained during laboratory tests and simulation. In quadrature voltage, the full range simulation and measurement cases are convergent. Some differences result from the different parameters of the systems supplying the laboratory. Measured values of the internal impedance of both systems were used in the simulation as an average value for all three phases. This is confirmed by the gradient of the characteristic, which results from the circuit parameters (line impedance, supply system's internal impedances). Based on this comparison, the authors accepted the model as validated and prepared the next analyses for APST and SPST devices.

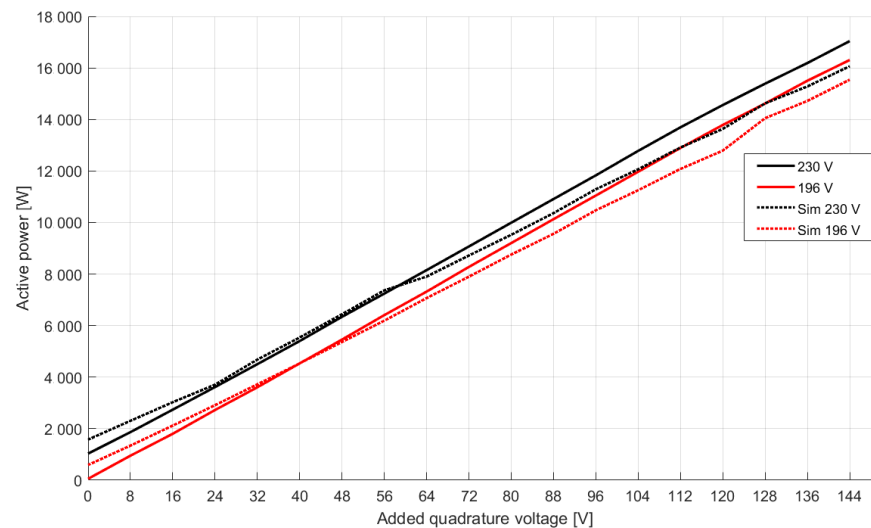


Figure 12. Comparison of transferred active power during laboratory tests (continuous line) and simulations (dotted lines).

5.2. SPST, APST, and ACPST Simulations

In this analysis, the authors prepared simulations of SPST, APST, and ACPST for 196 V and 230 V. Figure 13 presents the active power transfer in the line with each analyzed PST.

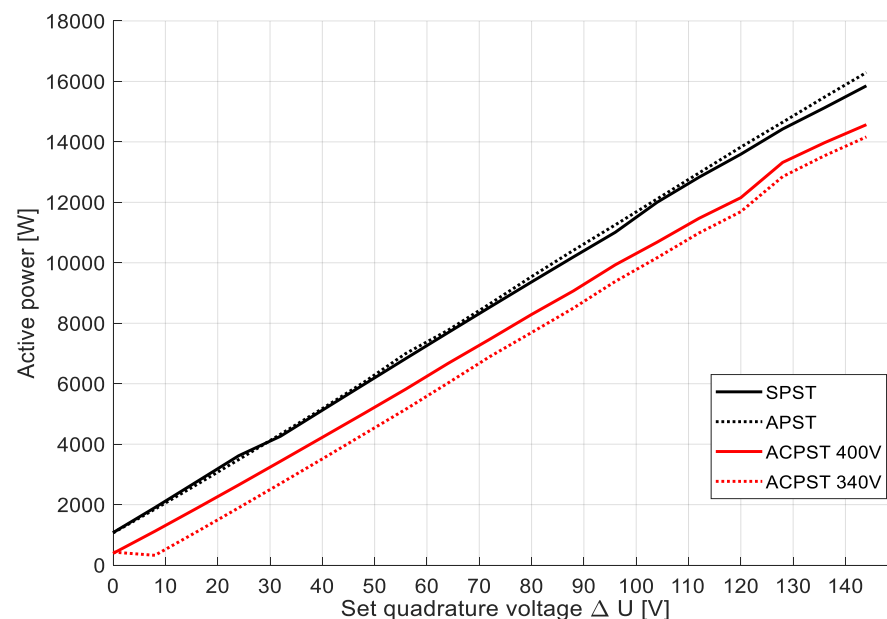


Figure 13. Active power transfer for different PSTs as a function of the set quadrature voltage.

Both SPST and APST guarantee the highest active power flow for the same set quadrature voltage. This is a result of both systems' nominal voltage values, because both SPST and APST operate on the natural voltage conditions in the system. The ACPST case works in the lowered or nominal line voltage, so these values are lower than in the rest cases. This fact is confirmed in Figure 14, representing output voltage waveforms for all cases.

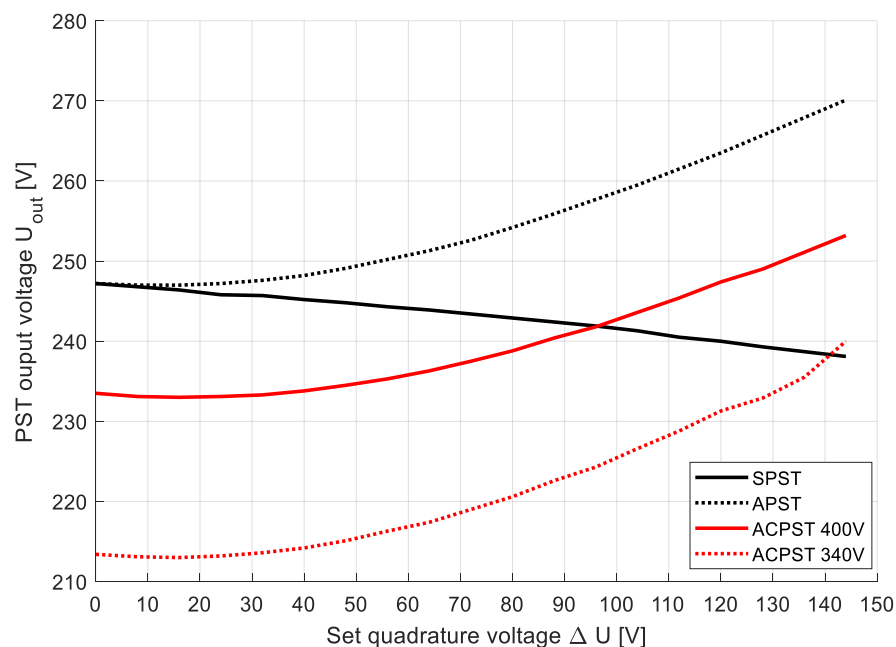


Figure 14. PSTs' output voltages versus set quadrature voltages.

All asymmetrical PSTs have a common feature. While the set quadrature voltage increases, the output voltage also increases. This is a natural consequence of their construction. Opposite to asymmetrical units, the SPST output voltage slightly decreases. This is a consequence of the voltage drops in the system due to greater current for higher quadrature voltages. Additionally, Table 3 collected the system voltage and SPST output voltage as a comparison of its symmetrical operation (both voltages have similar values). The highest set quadrature voltages are visible with the highest differences between analyzed voltages (for 144 V, the voltage drop is equal to 2.6 V). This relation is connected to the increase in the current flow and, consequently, voltage drops.

Table 3. Comparison of the system voltage and the SPST output voltage for considered quadrature voltage range.

ΔU	0	8	16	24	32	40	48	56	64	72
U_S	247.3	247.1	246.8	246.5	246.3	245.9	245.6	245.3	244.9	244.5
U_L	247.2	246.8	246.4	246	245.7	245.2	244.8	244.3	243.9	243.4
ΔU	80	88	96	104	112	120	128	136	144	
U_S	244.2	243.8	243.4	242.9	242.5	242	241.7	241.2	240.7	
U_L	242.9	242.4	241.9	241.3	240.5	240	239.3	238.7	238.1	

Figures 13 and 14 allow for comparing the active power flow regulation possibility by taking into account the set quadrature voltage and output voltage. Considering both parameters, ACPST definitely has the best properties. The small active power values range indicates that a transfer of 1.9 kW for SPST and APST requires 8 V injected into the line, while ACPST needs 16 V and 24 V for the 230 V and 196 V cases, respectively. Looking at the highest transferred active powers, it is visible that this tendency is maintained. The APST

transfers higher power than SPST, although insignificantly. Nevertheless, the difference in the output voltages is very high. The APST output voltage value is over 270 V for the 144 V case. For the same quadrature voltage, ACPST's 230 V case has 254 V on the output terminals, and in 196 V, one is almost 238 V.

For all PST devices considered in this research, the obtained angles α are relatively small. The maximum value for the SPST case was equal to 37° . This fact does not allow us to check the real angle curves because theoretical angle waveforms are prepared in a broader range of angles. Figure 15 shows the angle values for the injected quadrature voltages from 0 to 144 V.

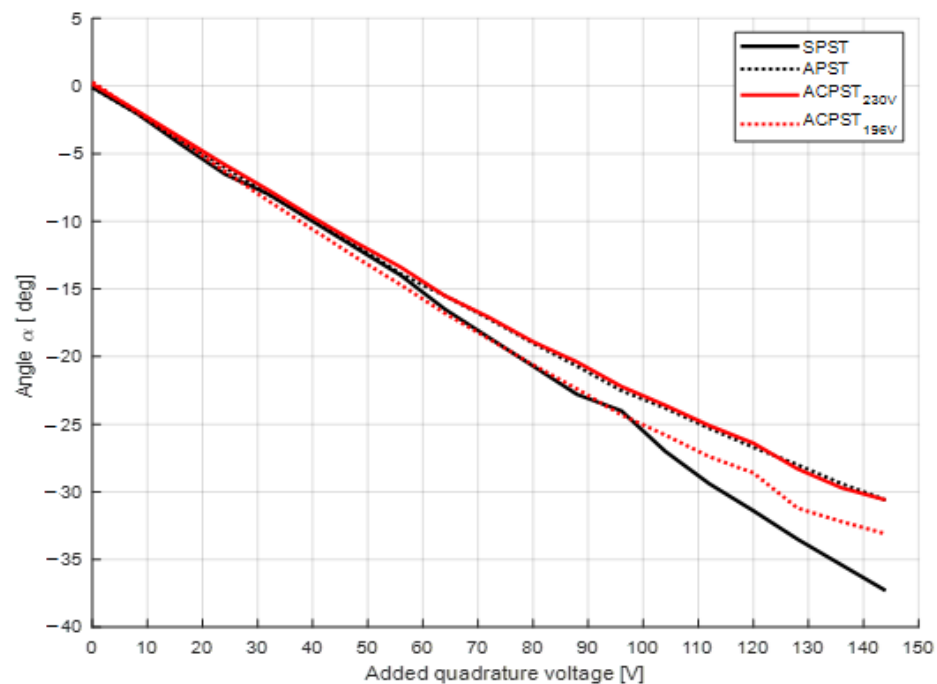


Figure 15. Angle α versus injected quadrature voltage for SPST, APST, and both ACPST cases.

The ACPST 230 V case and APST have very similar courses. The ACPST 196 V case shows that lowered longitudinal voltage allows for obtaining higher angle values, which confirms the theoretical assumption. The highest angle α is obtained for the SPST type; however, this dependency is visible for quadrature voltages greater than 100 V. This fact is connected to the voltage drops in the ACPST impedance, which is higher than in the SPST. The confirmation of this thesis is presented in Figure 16. The real quadrature voltage versus the set quadrature voltage clearly shows that SPST can maintain the real voltage injected into the line. For a maximum set value of 144 V, there is a 2 V drop, and the real quadrature voltage is equal to 142 V. In contrast to SPST are all the asymmetrical PSTs. Above a set quadrature voltage of 60 V, the voltage drops are higher than in the SPST case. For the maximal set quadrature voltage, the real quadrature voltage is 130 V for the ACPST type and 128 for the APST.

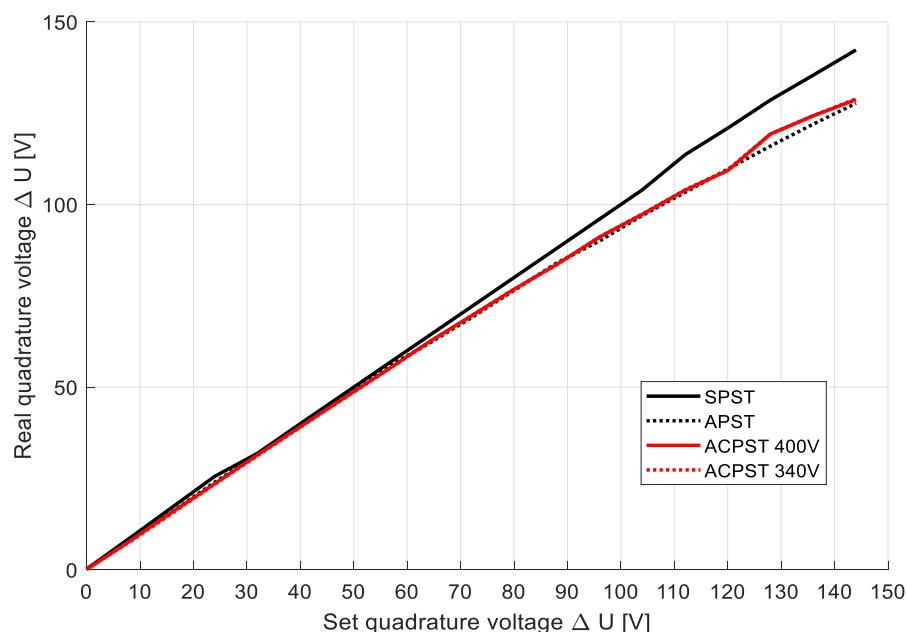


Figure 16. Real quadrature voltage versus set quadrature voltage for all PSTs.

6. Discussion

The presented results of the laboratory measurements and simulations for the ACPST case show that the prepared model is convergent with a real system. Based on this, preparation of the APST and SPST models was also possible.

Considering only the ability of the active power transfer for the chosen system configuration, it is visible that SPST and APST have better properties than ACPST. However, in the case of the APST, there must be information added about the APST output voltage value for the highest transmitted active powers. However, it is not acceptable for this system (the output voltage value is higher than 270 V, while the nominal phase-to-ground voltage is 230 V). This dependency is consistent with the asymmetrical PST theory, which points out that the APST output voltage value is always greater than the input one. This disadvantage can be efficiently liquidated by the ACPST construction, enabling longitudinal and quadrature voltage regulation. The tests conducted proved that it is possible to obtain similar power flow in the ACPST as in the APST case by adding higher quadrature voltage to lowered longitudinal line voltage. Furthermore, these regulation possibilities may be used to obtain higher angle α values, and in this way, influence the transmitted power parameters.

The SPST type, for the given assumptions, has the best properties concerning the electric power transmission parameters. It achieved the highest angle α for the same added voltages, the real quadrature voltage was almost equal to the set one (for 144 V, the real quadrature voltage was 142 V), and the problem with the PST output voltage increment was also omitted, as is shown in Figure 14 and Table 3.

The APST is able to transfer high power; however, as it was mentioned before, this is occupied by the output voltage value. This is not an acceptable feature because the regulation range can be widely reduced, especially in the power systems nodes, where voltages may be above nominal ones. As a consequence, the angles α possible to obtain are smaller than in the other PST types.

A solution enabling high active power transfer with simultaneous output voltage control is presented in ACPST construction. It allows controlling both longitudinal and quadrature voltages, which is the most important feature compared to the classical constructions of APST or SPST widely used in the literature. Longitudinal voltage regulation influences the angle α values and output voltage. Active power transfer for the given voltages is lower than in the SPST and APST. Conducted measurements and simulations

claim that it is possible to obtain the same active power flow by adding 8–24 V higher quadrature voltage for 230 V and 196 V cases, respectively. In some ranges (until c.a. 100 V of quadrature voltage for $U'S = 230$ V and 140 V for $U'S = 196$ V), the output voltages are smaller than in the SPST type, so the higher voltage injection does not worsen voltage parameters and enables an equal power flow as in the SPST.

The ACPST allows more flexible adjustment to the power system conditions, which is especially important in areas with variable voltage profiles. Nowadays, more and more renewable energy sources are installed in different grid areas on different voltage levels. This, taking into account the possible lack of remote electrical energy sources, or the opposite situation with its maximal amount, may expose the system to serious danger. A flexible device that controls power flows is needed, and the ACPST analysis clearly shows that it has comparative properties to the widely used SPST or APST units, but the regulation range is much greater.

For all considered cases, it should be noted that the results are obtained for low-voltage PST unit parameters, used as a base point for simulations. The relation between inductive reactance and resistance is different in the extra high voltage (EHV) power systems. However, regardless of the voltage level, any PST idea is the same.

The most important electric parameters and the impact of the chosen PSTs are displayed in Table 4. The ACPST has the best properties due to the wide regulation possibilities presented in the results section. The main disadvantage of this device is the need for two transformers. However, this problem may be solved soon in future research.

Table 4. The comparison of the considered PST.

Parameter	ACPST	APST	SPST
Active power regulation	Yes	Yes	Yes
Reactive power regulation	Yes	Yes *	No
Voltage increment	Yes	Yes	No
Voltage decrement	Yes	No	No
Angle regulation range	$\pm 90^\circ$	$\pm 90^\circ$	$\pm 90^\circ$

* Reactive power regulation is not independent as in case of ACPST.

7. Conclusions

This article describes the comparative analysis of the symmetrical, asymmetrical, and in-phase asymmetrical (called asymmetrically controllable) phase shifting transformers installed in a cross-border transmission line connecting two power systems. As a base for the research, two laboratory transformers were used, which create the laboratory ACPST unit. Then the simulation model of the ACPST was built and compared with the laboratory measurements. Thanks to both arrangements' good convergency, the SPST and APST were also implemented in the simulation stage. Using the obtained results for all considered PST types, their influence on the active power transfer was analyzed with regard to other electric energy parameters.

The SPST seems to have the best properties. The APST can also influence the active power transfer and control the flows, but the output voltage is too high, which in some cases may be unacceptable. ACPST, for the same quadrature voltages, allows one to transfer smaller power, but the rest of the considered parameters are on the best level. The whole analysis, taking into account all of the presented data, indicates that ACPST can be a good alternative to the SPST, or fulfill its role even better, especially when the nodal voltage may vary frequently. Due to this, ACPST construction should be considered the most flexible PST unit, which is important in modern grids with connected renewable energy sources with a variable energy production profile.

The data collected in Table 4 clearly underline each PST type's advantages and possible operation utility. However, the proposed ACPST unit stands out among the other regulating devices.

This article presents an ACPST solution only as a testing version, and the next tasks are linked to its automatic regulation depending on the required active power flow, voltages, or power losses in the power system.

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