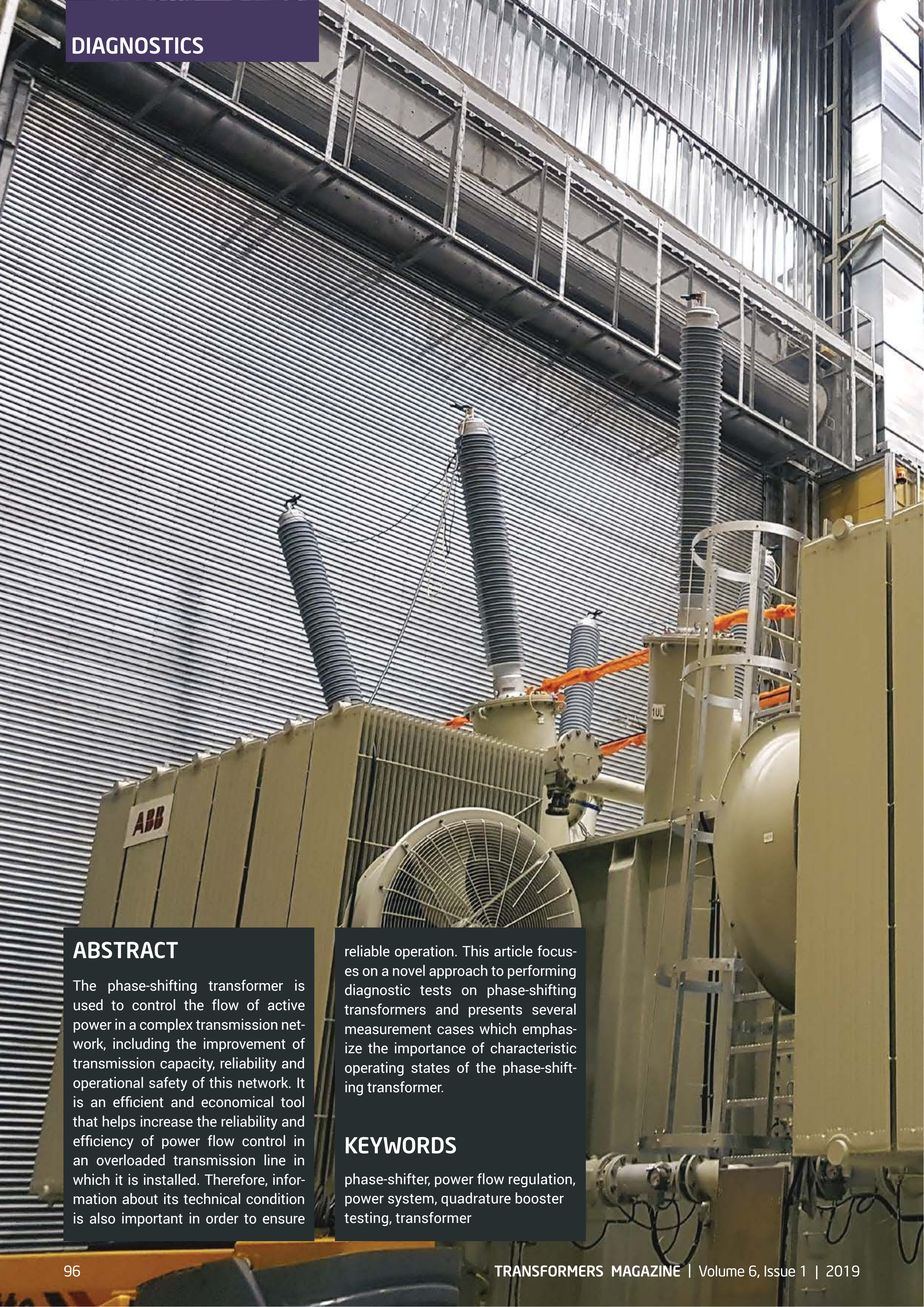


ABSTRACT

The phase-shifting transformer is used to control the flow of active power in a complex transmission network, including the improvement of transmission capacity, reliability and operational safety of this network. It is an efficient and economical tool that helps increase the reliability and efficiency of power flow control in an overloaded transmission line in which it is installed. Therefore, information about its technical condition is also important in order to ensure reliable operation. This article focuses on a novel approach to performing diagnostic tests on phase-shifting transformers and presents several measurement cases which emphasize the importance of characteristic operating states of the phase-shifting transformer.

KEYWORDS

phase-shifter, power flow regulation, power system, quadrature booster testing, transformer

Tomasz BEDNARCZYK, Cornelius PLATH, Adam JAROS

A novel approach to comprehensive tests on phase-shifting transformers

> **Phase-shifting transformers are used to control the power flow in a complex transmission network, improving transmission capacity, reliability and operational safety**

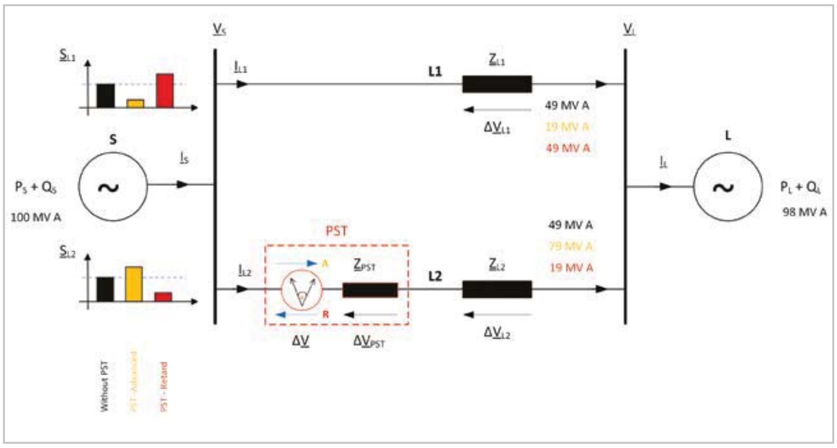


Figure 1. Basic circuit network diagram, double infeed, including power control via PST

> **The basic concept of phase angle adjustment is based on adding an additional voltage to the voltage present in the main path with a 90° phase shift**

1. Introduction

Today's power systems are usually not limited to one country or region, often comprising of multiple interconnected networks from different countries. These "cross-border" connections can either enable synchronous operation of multiple networks or establish a non-synchronous link between independently operated networks. The benefit of interconnected power systems is the mutual reservation of electric power which has become more important over the decades due to the increase of distributed energy resources (DER).

Concurrently, there are also disadvantages of interconnected power systems, such as unplanned circular flows, which can occur if the active power flow between subsystems cannot be controlled. These circular flows occupy part of the interconnection, which reduces the systems available transfer capability and thereby increases the losses. In critical situations, this may lead to a reduction of energy supply to consumers. One way to control this type of phenomena is the installation of phase-shifting transformers (PSTs) in synchronous connections. They are capable of controlling the power flow in the branch in which they are installed, thus affecting the change of power distribution in the network environment. This article focuses on the operational principle of a PST and some of the challenges during on-site and factory acceptance testing of these special types of transformers.

2. Principle of power regulation

The basic principle of power regulation using a PST can be explained by a simplified network. Consider a 100 MVA source (S) connected to the load (L) via two parallel power lines (L1 and L2) with their respective line impedances (Z_{L1} and Z_{L2}). The losses along the line are determined by the line parameters and result in a phase shift between the source- and load-side voltages. Given that Z_{L1} and Z_{L2} are equal, the power transmitted via both power lines will be evenly distributed. In such a system, the power will always be distributed according to the line parameters and cannot be regulated. Therefore, PSTs are used to introduce an additional phase shift between the load and source, in order to regulate the power flow across both lines.

In general, depending on the type of the PST, it is possible to regulate the flow of active and reactive power (depending on the PST construction):

$$S = \frac{|U_S|\cdot|U_L|}{X_L}\cdot\left[\sin(\alpha)+j\cos(\alpha)-\frac{|U_L|}{|U_S|}\right] \quad (1)$$

Dependence of transmitted active and reactive power (1) taking into account the PST:

$$S_{PST} = \frac{|U_S|\cdot|U_L|}{X_L + X_{PST}}\cdot\left[\sin(\alpha+\varphi)+j\cos(\alpha+\varphi)-\frac{|U_L|}{|U_S|}\right] \quad (2)$$

where U_S is the source side voltage S; U_L is the load side voltage L; X_L is reactance of the line (circuit) in which the PST has been installed; X_{PF} is the internal PST reactance; α is the phase angle between systems.

In the given example, a negative phase shift is introduced in the branch whereby the shifter is installed by placing the PST in the retard position which decreases the power transmitted in this branch. Due to the fact that the sum of the power transmitted across both lines remains the same, the power in the other branch increases. By placing the PST in the advance position and introducing a positive phase shift, the power distribution is completely opposite to the previous case. This time, the power flowing in the branch where the PST is located increases, while the power in the branch without the PST is reduced.

The example above only illustrates active power regulation by means of adjusting the phase angle, which is usually referred to as symmetrical regulation. It is, in addition, possible to regulate the flow of reactive power, which can be achieved by influencing the ratio between the source and load voltage. PSTs which regulate both active and reactive power are referred to as asymmetric phase-shifting transformers. For the purpose of this article, the discussion will be limited to symmetrical PSTs.

3. Operating principle of the symmetrical PST

The basic concept of phase angle adjustment is based on adding an additional voltage to the voltage present in the main path with a 90° phase shift (quadrature voltage, $\Delta\underline{U}$). Depending on the magnitude and polarity of the induced voltage, the phase angle can be adjusted. For this purpose, PSTs are used and usually consist of two transformers – A series unit and an exciting unit interconnected in a way that allows phase adjustment between the source and the load side. The construction example in the symmetrical single-stair version is described in Figure 2.

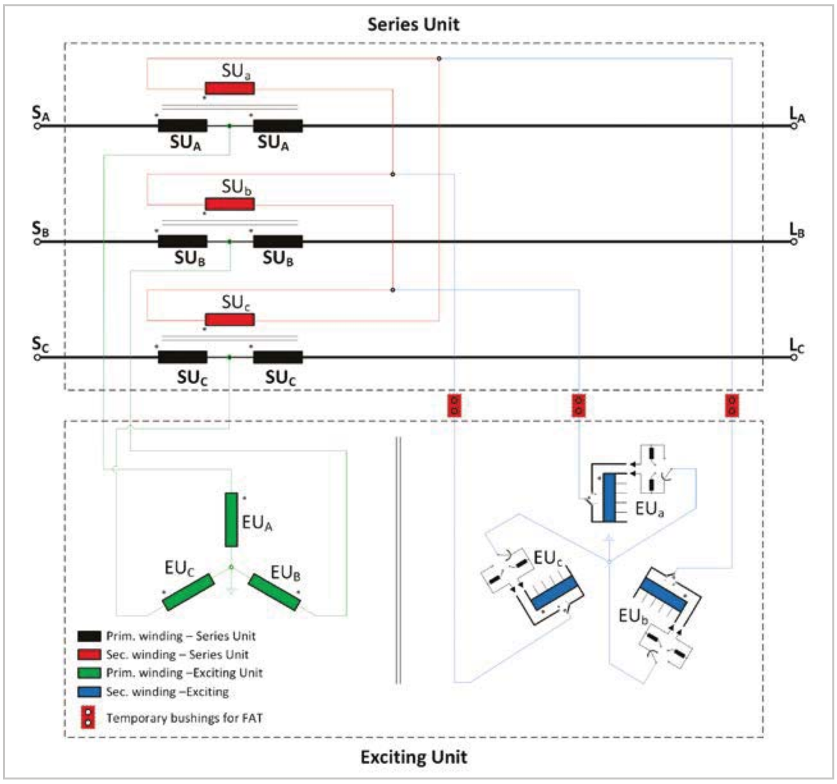


Figure 2. The wiring system of the symmetrical phase shifter windings

> **As the terminals of the EU are not accessible on site, individual tests of the EU are usually only possible in the factory**

3.1.Series unit

The series unit (SU) is the main element of the PST, whose primary winding is connected in series to the power line between the source *S* and load *L*. In the symmetric PST version, the primary winding SU consists of two parts divided symmetrically between the sides *S* and *L*. Between the two separated parts of the primary winding, the SU is connected to the primary winding of the exciting unit (EU), Figure 2. The secondary winding of the SU is connected in delta with the secondary winding of the EU to introduce a voltage shifted by 90° compared to the supply voltage.

3.2. Exciting unit

The purpose of the exciting unit (EU) is to transform the voltage derived by the primary winding of the SU in amplitude and phase angle, so that it can be re-induced by the secondary winding of the SU. Therefore, the primary winding of the EU is connected between the symmetrically separated coils of the SU primary winding, Figure 2. Such a connection enables the phase adjustment between *S* - *L* without changing the amplitude of the load side voltage UL. To regulate the magnitude of the quadrature voltage

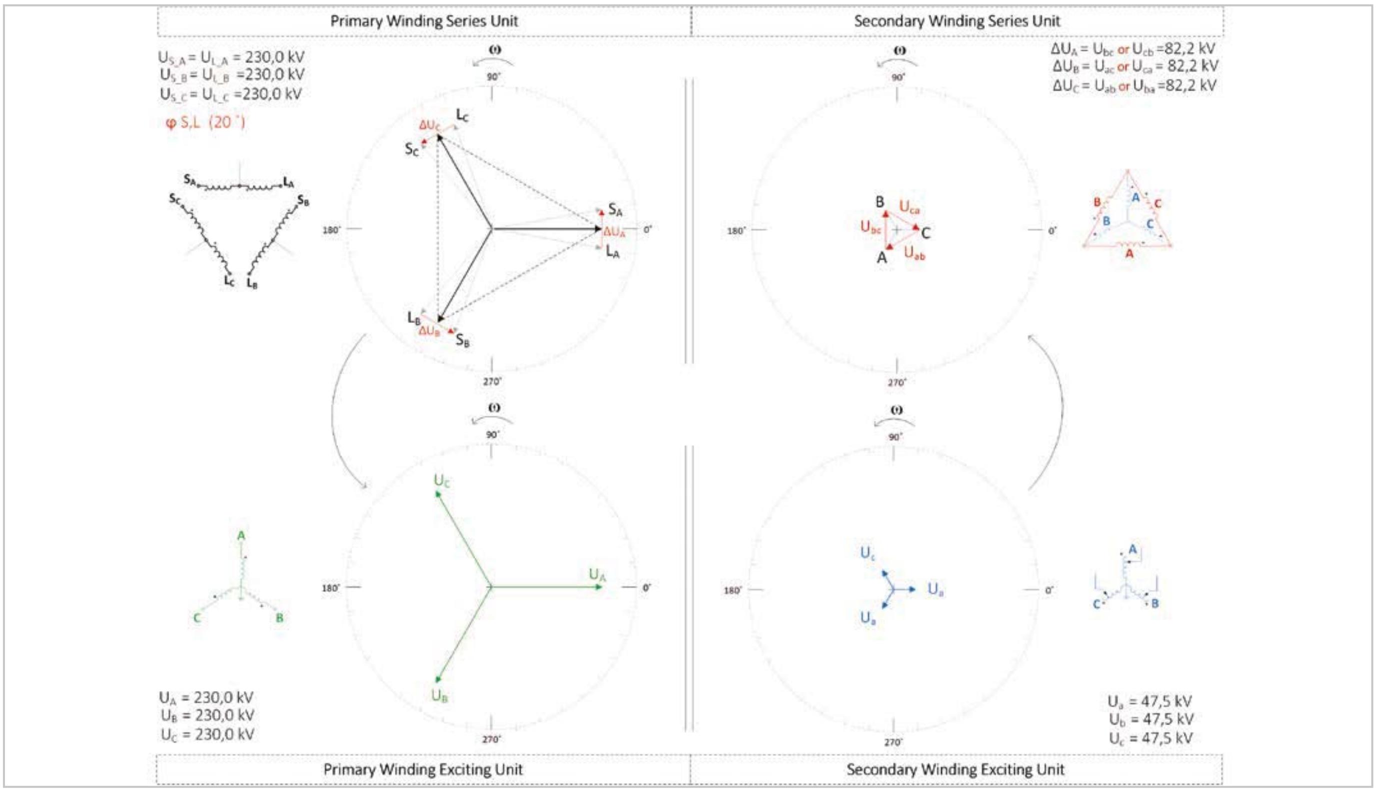


Figure 3. Vector diagram of voltages at individual stages of transformation for the unload PST state

Table 1. Selected electrical tests on PSTs for factory acceptance testing (FAT) and on-site testing

Measurement	Series Unit	Exciting Unit
Voltage turns ratio	FAT / On-site	FAT
Exciting current	FAT / On-site	FAT
Phase shift	FAT / On-site	FAT
DC Winding resistance	FAT / On-site	FAT
DC Dynamic winding resistance (OLTC Scan)	FAT / On-site	FAT

A portable three-phase transformer test system is used to perform a simultaneous measurement of the phase shift, voltage turns ratio and exciting current of all three phases

Figure 4. One-time connection of the three-phase transformer test system to perform all electrical tests according to Table 1

and therefore the phase angle between the source and load side of the PST, the secondary winding is equipped with an on-load tap-changer (OLTC).

To illustrate the principle of the quadrature voltage introduction, Figure 3 presents a number of vector diagrams at different operational stages of the transformation. Voltage values shown are for symmetrical PST with a nominal voltage of 400 kV and adjustment angle ± 20° [1]. The colours of the windings in Figure 2 are the same as the colours of the vectors in Figure 3.

The standard [2] distinguishes between two types of phase shifters, depending on whether the series and the exciting unit are housed in two separate or one single tank. Regardless of the selected design, the idea of operation is always the same – the difference lies in the implementation of the voltage ΔU, as well as in the advantages and disadvantages of the solution. When choosing the type of PST structure, many aspects are taken into consideration, but the most often deterministic parameter is the transitive power.

4. Phase-shifting transformer tests

When PSTs are installed in the field, the terminals of the EU are usually not accessible. While it is common to install temporary bushings for the purpose of testing during factory acceptance, this option rarely exists during on-site field testing. Therefore, individual tests of the EU are usually only possible in the factory. Table 1 lists several electrical tests which are part of standard acceptance testing of the series and exciting units. It shall be noted that Table1 lists tests which have been chosen in the context of this article because they are suited to show the characteristic behaviour

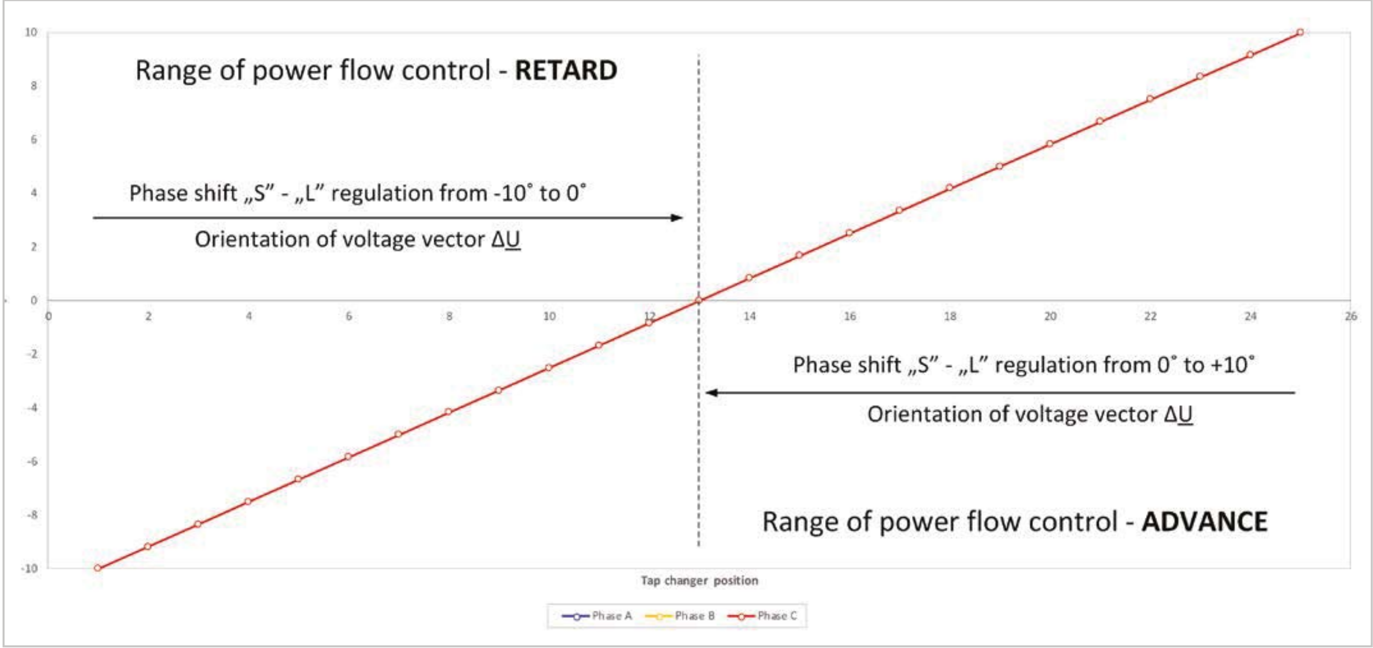


Figure 5. The results of the phase shift measurements "S" - "L" as a function of the OLTC position of the excitation unit

> **A big challenge on site is to determine whether the PST is operating in advance or retard position, i.e. whether it is enhancing or blocking the power flow in the respective branch**

of PSTs and are usually part of any factory acceptance or on-site test procedure. However, they do not represent the complete list of tests that may be performed. In our case, the test object is a 500 MVA, 230 kV, symmetrical IIId/YNyn0 transformer, with a phase-shifting range between -10° and +10°. This means that the primary winding of the series unit is connected in series (III) and the secondary winding is connected in a delta (d) without a phase shift. The primary and secondary side of the exciting unit are both connected as a wye with neutral connection (YNyn) and a 0° phase shift between the two sides. The phase shift between -10° to +10° between the source and load side terminals is only achieved by the introduction of the quadrature voltage.

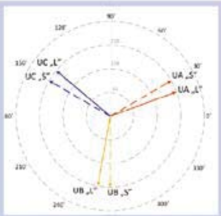
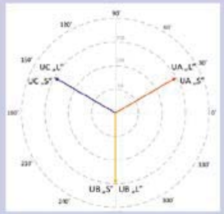
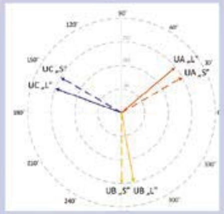
4.1. Series unit measurement

Analog to measuring the voltage ratio at different tap positions of a common network transformer, it is important to verify the specified phase-shifting range between the line terminals of the *S* and *L* sides of the PST.

In this case a portable three-phase transformer test system, as illustrated in Figure 4, is used to perform a simultaneous measurement of the phase shift (see Figure 5), voltage turns ratio (see Figure 6), and exciting current of all three phases. The results confirm the operating range between +10° and -10° and a step width of 0.87° under no-load condition.

A big challenge for testing engineers, especially during commissioning testing on site, is to determine whether the PSTs are operating in advance or retard position, that is, whether the PSTs are enhancing or blocking the power flow in the respective branch, Figure 1. This is required to define the source and load side terminals. Using a three-phase measurement, the phase relation of the source and load side voltages and currents can conveniently be displayed in a vector diagram to determine the state of the control. An example of the results obtained at different tap positions is shown in Table 2.

Table 2. The results of phase shift measurements *S* - *L* for three characteristic positions

Channel	Phase shift 10°		Phase shift 0°		Phase shift -10°	
	Value	Phase	Value	Phase	Value	Phase
UA "S"	250 V	30°	250 V	30°	250 V	30°
UB "S"	250 V	-90°	250 V	-90°	250 V	-90°
UC "S"	250 V	150°	250 V	150°	250 V	150°
UA "L"	250 V	20°	250 V	30°	250 V	40°
UB "L"	250 V	-100°	250 V	-190°	250 V	-80°
UC "L"	250 V	140	250 V	150°	250 V	160°
						
	UA "S" UB "S" UC "S" UA "L" UB "L" UC "L"					

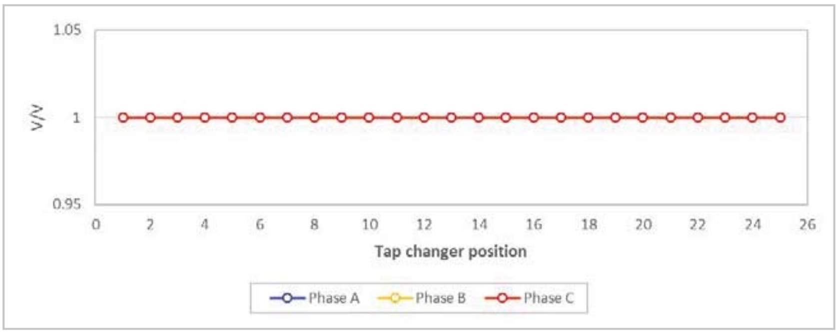


Figure 6. Measurement results of the voltage ratio *S* - *L* of the serial unit as a function of the OLTC position of the excitation unit

Using a three-phase transformer test system is a very fast and efficient way to verify the operation parameters of PSTs during commissioning and maintenance in the field

The vector interpretation of the measurement results of the phase shift control direction gives an unambiguous indication of which voltage vector of the S or L side is delayed or ahead of the other. Thanks to this visualization of the measurement results, an additional oscilloscope recording which would require additional equipment and increase the testing time is not required.

It is possible to determine the mathematical values of the additional voltage ΔU which should be introduced between the US - UL voltage vectors to obtain the desired phase shift [3]:

$$\Delta U = \frac{2 \cdot U_{LL}}{\sqrt{3}} \cdot \sin\left(\frac{\varphi}{2}\right), \qquad (3)$$

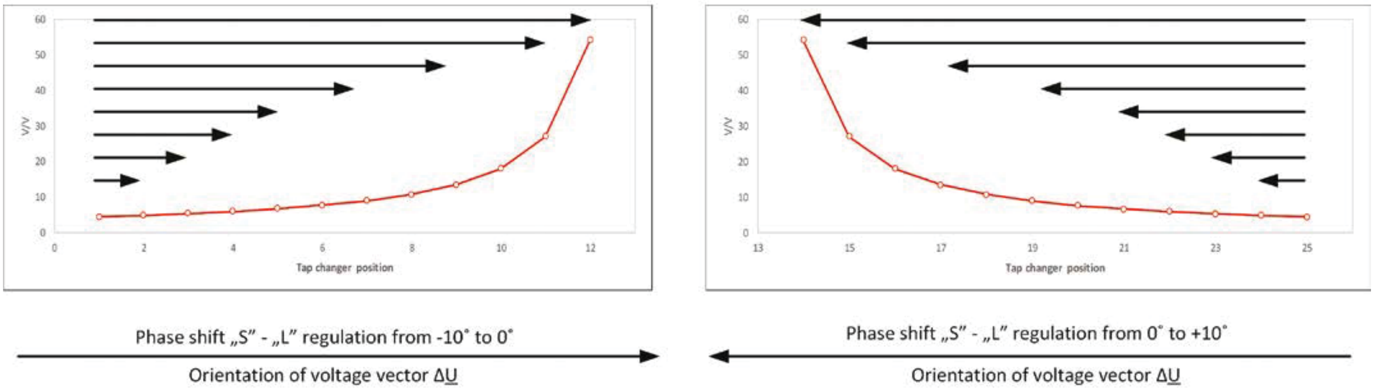


Figure 7. Measurement results of the voltage converter of the excitation unit as a function of the OLTC position

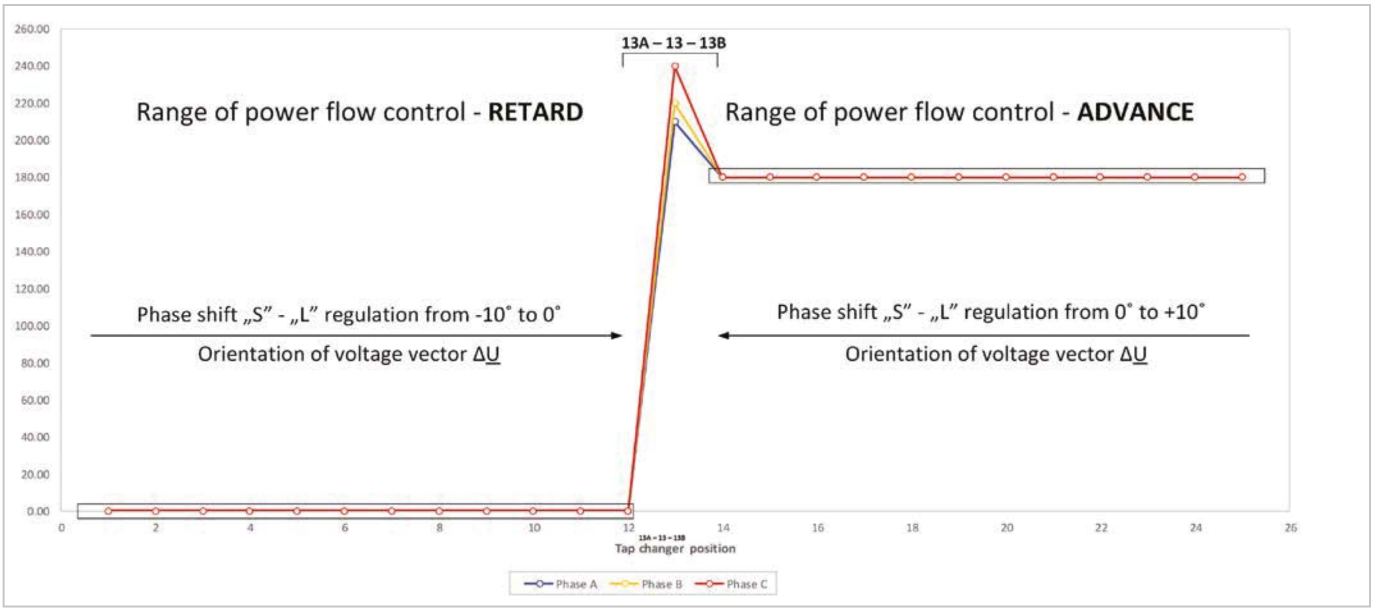


Figure 8. Results of phase shift measurements of the excitation unit as a function of the OLTC position

where U_{LL} equals PST phase-to-phase voltage, and φ is the expected phase shift between S - L.

The voltage value ΔU will be calculated for the PST analyzed as well as the exemplary two control positions of the 5° and 10° phase:

$$\Delta U_{5^\circ} = \frac{2\cdot 220}{\sqrt{3}}\cdot \sin\left(\frac{5}{2}\right) = 11.08\ \text{kV} \tag{4}$$

$$\Delta U_{10^\circ} = \frac{2\cdot 220}{\sqrt{3}}\cdot \sin\left(\frac{10}{2}\right) = 22.014\ \text{kV} \tag{5}$$

By measuring the ratio between the *S* and *L* side of the SU, it is possible to identify the type of PST under test. A constant voltage ratio over the entire phase-shifting range, Figure 6, is indicative of the symmetrical PST. This is caused by the fact that the voltage ΔU (see Figure 3) is introduced between the symmetrically divided coils of the main winding (as in Figure 2). A change in phase angle and ratio would indicate an asymmetrical regulation, that is, adjustment of both active and reactive power.

4.2. Exciting unit measurement

The first measurement for the EU is to check the voltage ratio for all tap-changer positions. By changing the voltage ratio of the EU, the magnitude of the quadrature voltage and, thus, the phase shift between the source and the load side can be adjusted. Figure 7 shows the ratio changing between 4.52 to 54.19 for positions 1 through 12 and vice versa for positions 12 through 25. Positions 13A through 13B are the positions of the change-over selector to switch the polarity of the regulating winding, as shown in Figure 8.

Although, according to the nameplate, the phase shift of the EU is denoted with 0 – 0°, the change in polarity is clearly visible when measuring the phase shift between the two windings for vector group 6 – 180°, Figure 8. This change in polarity is required to operate the PST in either advance or retard position.

Conclusion

Phase-shifting transformers (PSTs) are an important part of today's synchronous power networks. Due to the changing generation infrastructure, they are likely to play an even more important role in ensuring the reliability of power grids in the future. As PSTs are usually installed at critical nodes in the network, the time for off-line maintenance is very valuable. The results have shown that using a three-phase transformer test system is a very fast and efficient way to verify the operation parameters of PSTs during commissioning and maintenance in the field. By looking at an example of the symmetrical PST, we have shown how the operation principle as a combination of series and exciting units can be easily verified during factory acceptance testing. The same approach can also be used for the asymmetrical PST.

Bibliography

[1] T. Bednarczyk, M. Szablicki, A. Halinka, P. Rzepka, *Structure of the Automatic Protection of a 2-Tank Symmetric Phase-shifting Transformer*, Acta Energetica 32/2018

[2] IEC 60076-52-1202:2017, *Power transformers – Part 57-1202: Liquid immersed phase-shifting transformers*

[3] M.A. Ibrahim, F.P. Stacom, "Phase Angle Regulating Transformer Protection", IEEE Transactions on Power Delivery, Vol. 9, No. 1, January 1994

[4] *TESTRANO 600 User Manual*, OMICRON electronics GmbH 2018

Authors

Tomasz Bednarczyk obtained a diploma degree from the Electrical Department of the Silesian University of Technology in 2015. Currently he is a PhD student at the Institute of Electrical Power Engineering and Systems Control. His focus is research activities related to the analysis of the operating state of phase shifters in normal and disturbing operation conditions for the purposes of testing the correct operation of the power protection system. He has been professionally associated with the subject of station measurement of primary and secondary equipment for many years. Since 2017 he has been working for OMICRON electronics GmbH as an Application Engineer.

Cornelius Plath graduated with a diploma degree in Electrical Power Engineering and Business Administration from the RWTH Aachen University, Germany. During his studies he was involved with several industry funded research projects on condition assessment of electrical power apparatus at the Institute of High Voltage Technology. He joined OMICRON in 2010 as an Application Engineer and currently holds the position of Product Manager. He has vast international application experience, specializing in electrical diagnostics of circuit breakers and transformers.

Adam Jaros graduated with a diploma degree in Electrical Engineering from the Technical University of Lodz, Poland in 2003. From the very beginning of his professional career he has been associated with ABB Power Transformers Plant in Lodz as an engineer at the Test Field. Since 2009 he has managed the Test Field in ABB Power Transformers Division.