Topic

A novel approach to comprehensive tests on phase shifting transformers

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Phase shifting transformers are used to improve the transmission capacity, reliability and operational safety in complex transmission networks. In this article a novel approach to verify the operating parameters during factory acceptance and on-site field tests is discussed.

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 allows you to increase the reliability and efficiency of power flow control in an overloaded transmission line in which it was installed. Therefore, information about its technical condition is also important in order to ensure a reliable operation. The article focuses on a novel approach to perform diagnostic tests on phase shifting transformers and presents several measurement cases which emphasize the importance of the characteristic operating states of the phase shifting transformer.

Keywords: power system, power flow regulation, transformer, phase shifter, quadrature booster testing.

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 (PST) 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 PST and on some of the challenges during on-site and factory acceptance testing of these special types of transformers.

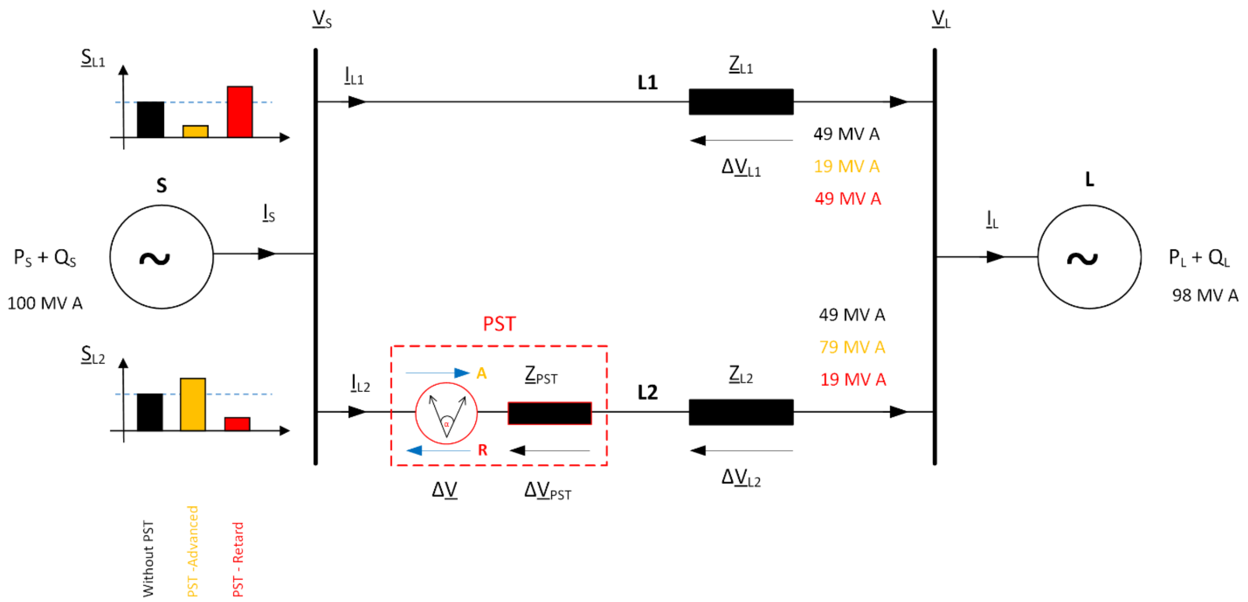


Figure 1. Basic circuit network diagram double infeed including power control via PST

2. Principle of power regulation

The basic principle of power regulation using 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, PST 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 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 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 - source side voltage "S"; U_L - load side voltage "L"; X_L - reactance of the line (circuit) in which PST was installed; X_{PF} - internal PST reactance; α - 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 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.

So far, the example has only discussed 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. PST 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 PST.

3. Operating principle of 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, Figure 3. For this purpose, PST 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-tank version is described in Figure 2.

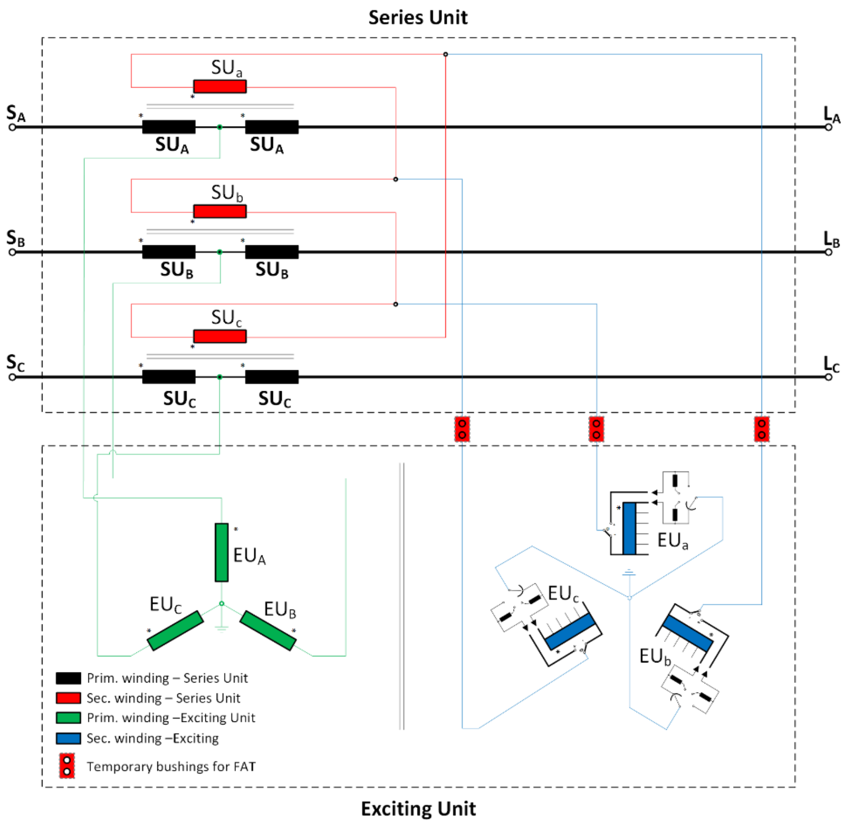


Figure 2. The wiring system of the symmetrical phase shifter windings

3.1 Series unit

The series unit (SU) is the main element of 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 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 4 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 colors of the windings (Figure 2) are the same as the colors of the vectors. Figure 3.

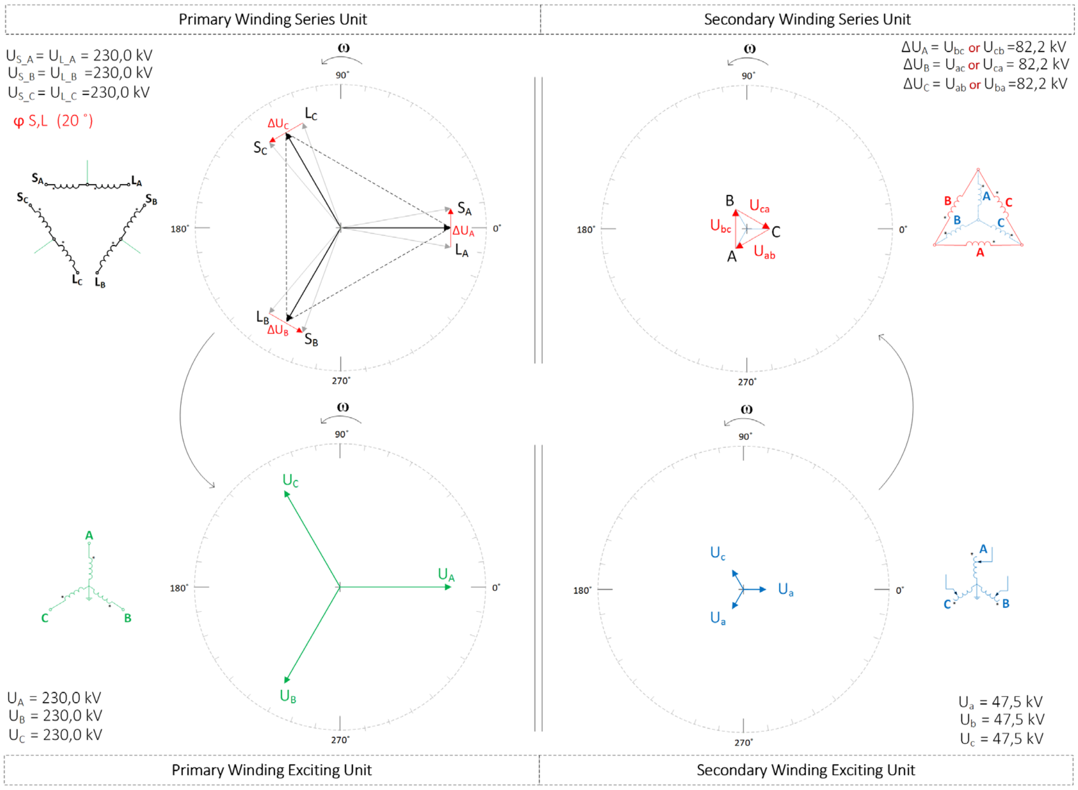


Figure 3. Vector diagram of voltages at individual stages of transformation for the unload PST state

The standard [2] distinguishes between two types of phase shifters, depending on weather 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 $\Delta \underline{U}$, 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 PST 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 Table 1 lists tests which have been chosen in the context of this article because they are suited to show the characteristic behaviour 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 deg 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. °.

Table 1. Chosen electrical tests on PST 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

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 PST.

Figure 4. One time connection of the 3-phase transformer test system to perform all electrical tests according to Table 1.

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

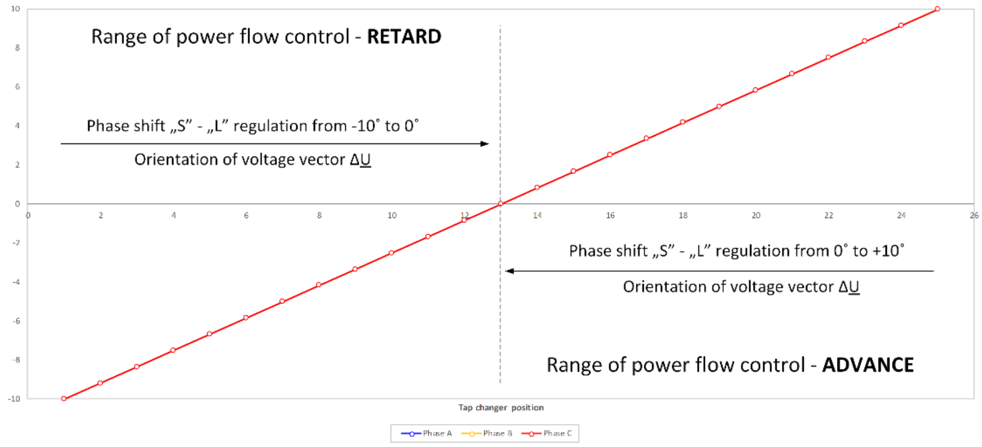
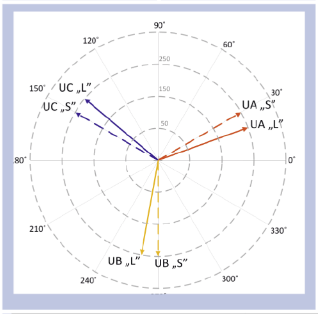
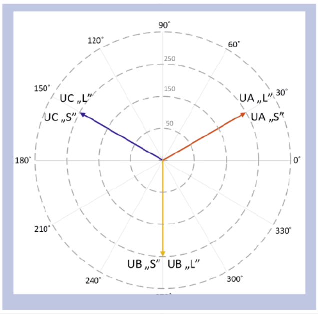
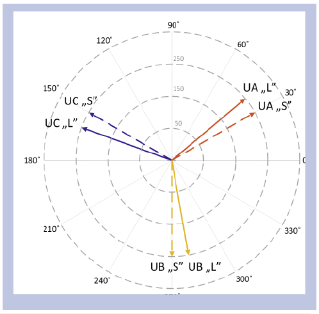


Figure 5. The results of the phase shift measurements "S" - "L" as a function of the OLTC position of the excitation unit

A big challenge for testing engineers, especially during commissioning testing on site, is to determine whether the PST are operating in advanced or retard position, that is, if the PST are enhancing or blocking 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"					

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]:

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

Where: U_{LL} - PST phase-to-phase voltage, φ - 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:

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

$$\Delta U_{10^\circ} = \frac{2 \cdot 220}{\sqrt{3}} \cdot \sin\left(\frac{10}{2}\right) = 22.14 \text{ kV},$$

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 symmetrical PST. This is caused by the fact that the voltage ΔU, Figure 3, is introduced between the symmetrically divided coils of the main winding, Figure 2. A change in phase angle and ratio would indicate an asymmetrical regulation, that is, adjustment of both active and reactive power.

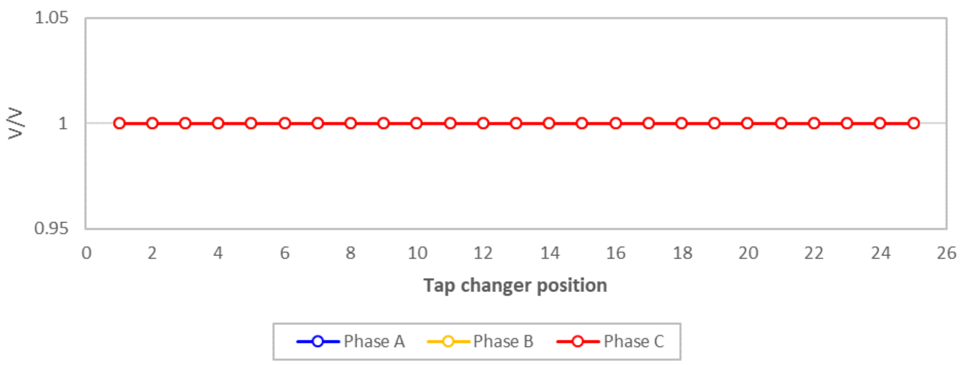


Figure 6. Measurement results of the voltage ratio "S" - "L" of the serial unit as a function of the OLTC position of the excitation unit

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, Figure 8.

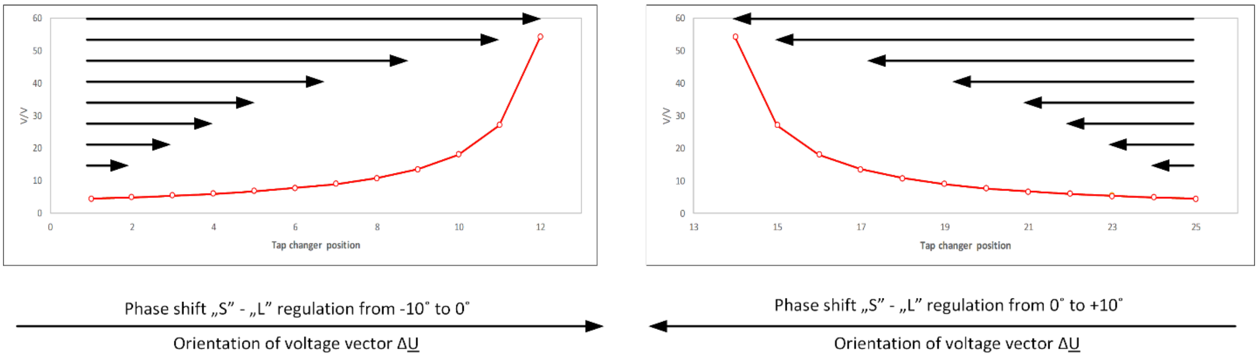


Figure 7. Measurement results of the voltage converter of the excitation unit as a function of the OLTC position

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 PST in either advance or retard position.

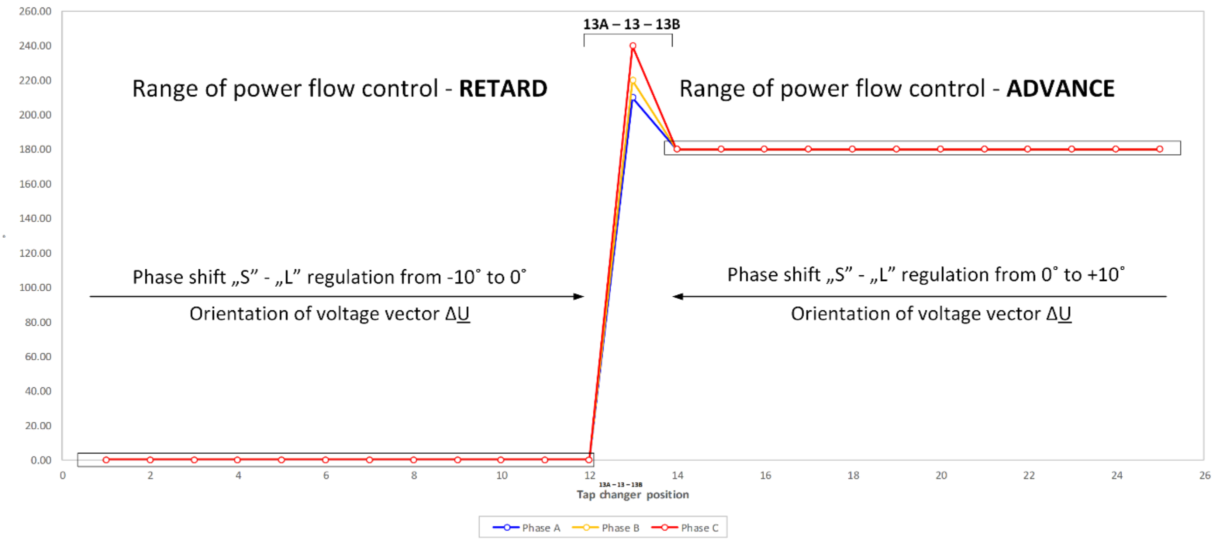


Figure 8. Results of phase shift measurements of the excitation unit as a function of the OLTC position

Conclusion

Phase-shifting transformers (PST) 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 PST 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 PST during commissioning and maintenance in the field. By looking at the example of 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 asymmetrical PST.

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Leads

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When choosing the type of PST structure, many aspects are taken into consideration, but the most often deterministic parameter is the transitive power

Therefore, individual tests of the exciting unit are usually only possible in the factory

In this case, 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

A big challenge for testing engineers, especially during commissioning testing on site, is to determine when the PST are operating in advance or retard position, which is required to define the source and load side terminals

A change in phase angle and ratio would indicate an asymmetrical regulation, that is, an adjustment of both active and reactive power

Biography

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.

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