> Using phase-shifting transformers for power flow control at grid interconnection points is not only a dependable but also a cost-effective solution

Phase-shifting autotransformer

Cost and energy efficient solution for managing energy flow

ABSTRACT

Transmission networks of different high voltage levels are usually connected by autotransformers. These autotransformers are generally continuous flux types regulated from the HV or LV side. Some cases also require controlling the power flow between these networks. One such case is in Ghana, where the existing 161 kV transmission network is expanded by new 330 kV lines. A cost effective and dependable solution selected by Ghana Authorities is the use of phase-shifting autotransformers. This article discusses the technical properties and design considerations of the 200 MVA 330/161 kV autotransformer installed in Ghana for this purpose in 2016.

KEYWORDS

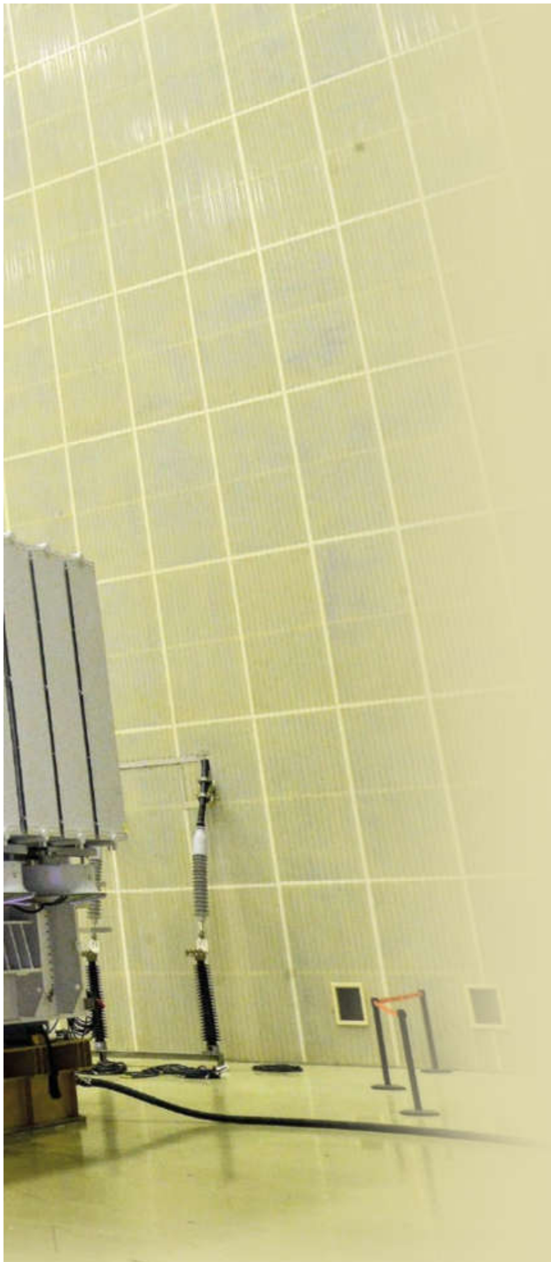
autotransformer, phase-shifting, power flow, interconnection

1. Introduction

Ghana Authorities decided to install 200 MVA 330/161 kV in-quadrature phase-shifting autotransformers (ATRs) which allow both network interconnection and power flow control. The choice to use a phase-shifting transformer instead of other methods, such as decreasing line reactance or using very low impedance transformers, was due to both the dependability of this solution and lower costs compared to other methods. This article discusses the features that distinguish phase-shifting autotransformers from other transformers, and provides an overview of their design, manufacture, and testing phases.

2. Overview of Ghana network and the need for power flow control

Ghana has recently started expanding its transmission network by adding 330 kV transmission lines. An important part of this shift is the new line between Prestea and Kumasi. With it, Ghana Grid Com-



Since their design is based on autotransformers, phase-shifting autotransformers have significantly reduced costs and losses

pany (GRIDCO) plans to improve power transfer capacity from the Aboadze generation enclave in the south to the western and northern parts of the country. The new lines will be running parallel to the existing 161 kV lines. In order to connect the 330 kV to the 161 kV busbars, 330/161 kV autotransformers, with voltage regulation on 161 kV side, will be utilised. However, the reactance of these two autotransformers in addition to the 330 kV line reactance means that the new 330 kV network's reactance will be too high compared to the 161 kV network. As a result, most of the power would continue to flow on the already overloaded 161 kV lines. A comparatively small portion would flow on the more efficient 330 kV lines, hindering its purpose of increasing transmission capacity. Therefore, a further measure to redirect the power flow to the new lines is needed.

2.1 Possible solutions for power flow control

Since the main reason for unbalanced loading of the lines is the difference in reactance, the most straightforward solution would be to decrease the reactance on the 330 kV lines in comparison to the 161 kV lines. There are technical limitations on how low line reactance can be decreased, which also creates a much higher initial investment, as special lines and carrier geometries would need to be involved. Even so, only reducing the line reactance is not enough by itself.

Along with the transmission lines, short circuit impedance of the ATRs to be purchased would also need to be very low. Designing autotransformers with very low impedance voltages has the risk of higher currents in case of short circuit, meaning higher susceptibility to its harmful effects. In addition, all equipment, including the ATR and the transmission lines, but also the protection equipment, would be designed for these higher currents and therefore have an increased purchasing cost.

The other method is to create a phase angle difference between the EHV (330 kV) and HV (161 kV) lines, by means of phase-shifters (PSTs) connected in series to the autotransformers. However, PSTs require their own connection, control and protection equipment, as well as space for installation in addition to the ATR. High purchase cost of PSTs should also be considered. Another concern is the added losses from the PST itself.

Phase-shifting autotransformers act on the same principles as PSTs, but they combine the main ATR with the PST, thus significantly reducing costs and losses.

2.2 Preferred solution

After a comparative evaluation of all possible solutions, phase-shifting autotransformers were selected for the purpose. The units installed on the Aboadze-Tema 330 kV line were of the same power and voltage rating – 200 MVA, 330/161 kV, with in-phase regulation of 161 kV±8·1.25 %, and in quadrature phase angle shift range of ±2·3° off-load. These were installed on both ends of the line to achieve the total necessary phase shift of 12.

More such transformers will similarly be installed on both ends of the Prestea-Kumasi line. Transformers are again 200 MVA, 330/161 kV±8·1.25 %. The in-phase regulation on the LV side is the same. But the in quadrature regulation is achieved by a reversing on-load tap-changer (OLTC), with 17 positions instead of just five like the older phase-shifting autotransformers installed in Aboadze. Of course, since the phase shifting winding is located on the common neutral of the transformer, turn-ratio is changed for each position. Further, the older transformer was specified with the opinion that power

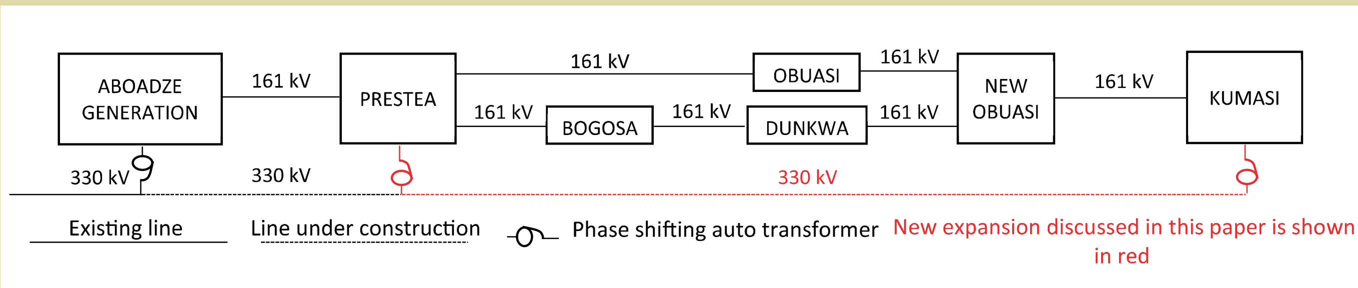
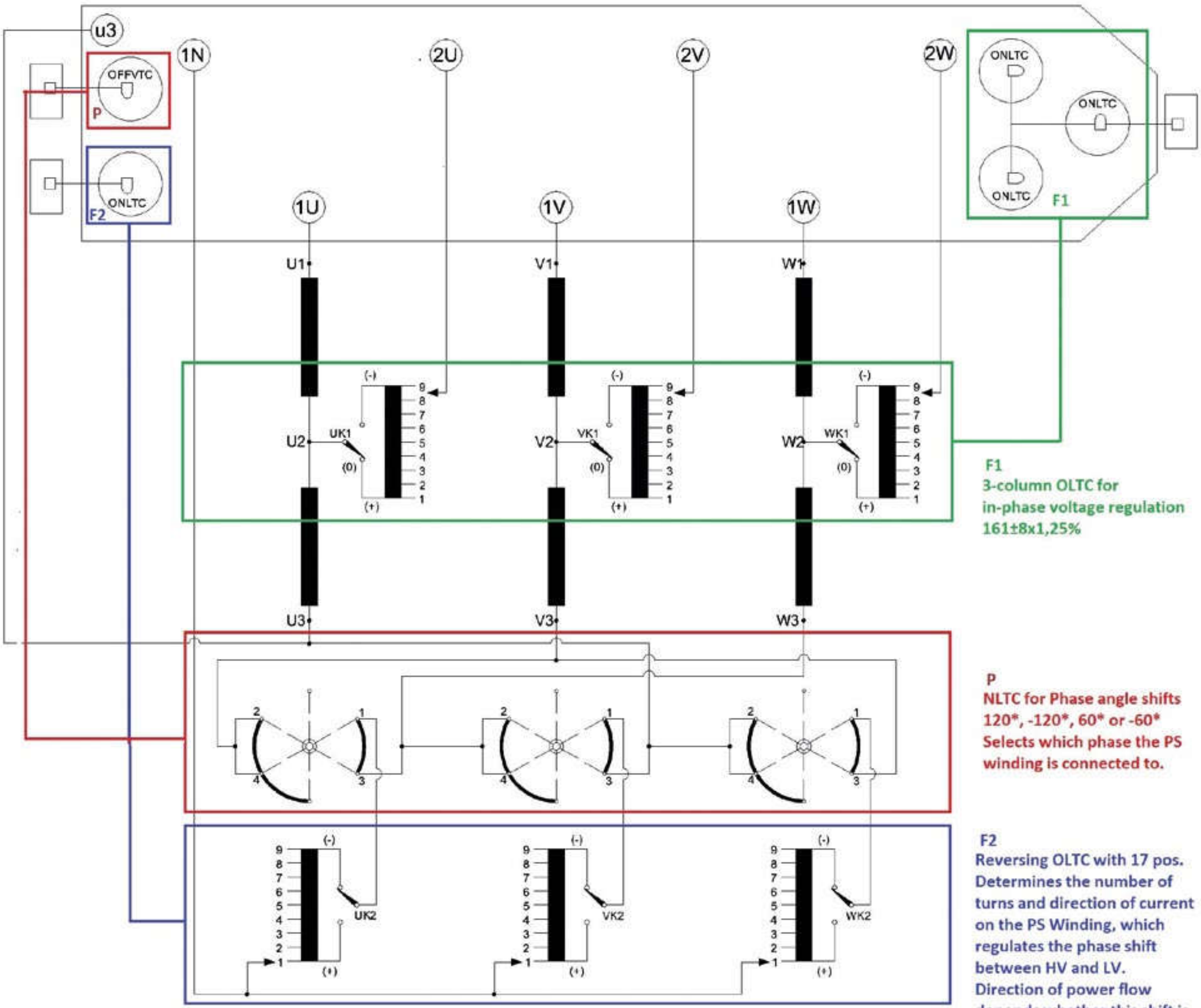
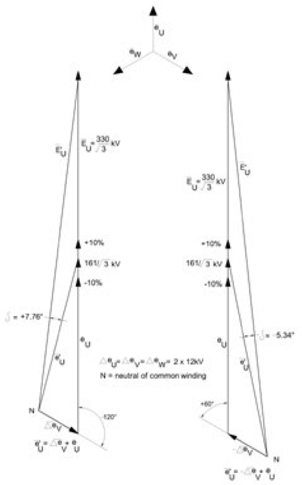


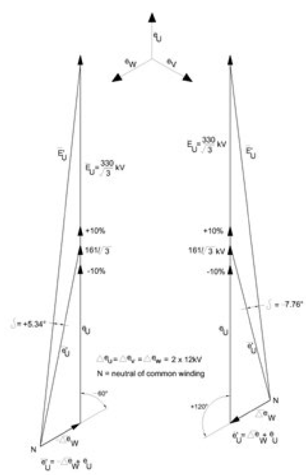
Figure 1. Simplified diagram of the transmission network between Aboadze & Kumasi



2a. Different OLTCs used in PST



2b. Vector phasor diagram in 120° for U phase:
PS winding on the U-leg is connected to W-phase;
PS winding on the V-leg is connected to U-phase;
PS winding on the W-leg is connected to V-phase.
On the left diagram, current flows normally through PS;
Phase angle is +7.76°;
Power flow is from 330 kV to 161 kV.
On the right diagram, current flow on the PS winding is reversed;
Phase angle is -5.34° and power flows from 161 kV to 330 kV



2c. Vector phasor diagram in -60° for U phase:
PS winding on the U-leg is connected to V-phase;
PS winding on the V-leg is connected to W-phase;
PS winding on the W-leg is connected to U-phase.
On the right diagram, current flows normally through PS;
Phase angle is +5.34°;
Power flows from 161 kV to 330 kV.
On the right diagram, current flow is reversed on the PS winding;
Phase angle is -7.76° and power flows from 330 kV to 161 kV.

Figure 2. Connection diagram and vector phasor diagrams of PST

flow direction changes would only occur seasonally, and thus, the phase shifts would only be conducted off-load. However, the new transformer allows both voltage regulation and phase shifting on-load.

Phase-shifting function provides an extra capacity added to the full autotransformer capacity

3. Phase-shifting autotransformer design study

The main principle behind the design of the phase-shifting autotransformer is adding the turns belonging to the phase winding of one core leg to the phase winding of the other core leg. This is done by means of phase-shifting (PS) regulation windings wound on each leg of the transformer. Through a no-load tap-changer (NLTC), the PS winding is then connected to the end of the parallel winding of another phase instead of the phase it is associated with; and this principle applies to all three phases. This means that the current with the phase shift will flow through the main winding. For example, to achieve a 120˚ phase difference, PS winding on the phase U is wound to the leg of phase V; phase V is wound to the leg of phase W; and PS of phase W is wound to the leg of phase U. In this way, depending on the number of turns on the PS winding, a phase difference between the HV and LV is created.

In our case, the PS winding is designed as a regulation winding. A reversing OLTC allows the phase shift angle to be fine-tuned. The more turns in use in the PS winding, the wider the phase angle between HV and LV. Direction of power flow depends on whether this phase angle is – or +, which is decided by both the phase the PS winding is connected to and the direction of current through the PS winding.

Since the phase-shifting autotransformers are used on both ends of the transmission line, the total phase difference that can be created is twice that of a single transformer's own phase shift range. With this arrangement, if for example one transformer is lagging 6° and the other is leading 6°, the total phase shift will be 12°.

It should be noted that since the PS winding is located on the common neutral, the transformer's volts-per-turn is changed when it is in use, which is referred to as Variable Flux Voltage Variation (VFVV) according to IEC 60076-1 Item 5.2 [1]. All the design complications for a VFVV type transformer have to be considered, and the main one among these is the fact that the core magnetic flux density changes at each tap. For this design, voltage on the HV side is considered a constant 330 kV.

The described phase-shifting function is an extra capacity added on the full autotransformer capability. It should be noted that the following properties do not subtract from this main function. As such, there is already an in-phase regulation tap-changer located on the LV line end. Different OLTCs and their uses are explained in Figure 2.

3.1 Voltage & phase regulation

Three different tap-changers used in the transformer each serve a different purpose:

- The ±8·1.25 % voltage regulation on the 161 kV side between 177 kV and

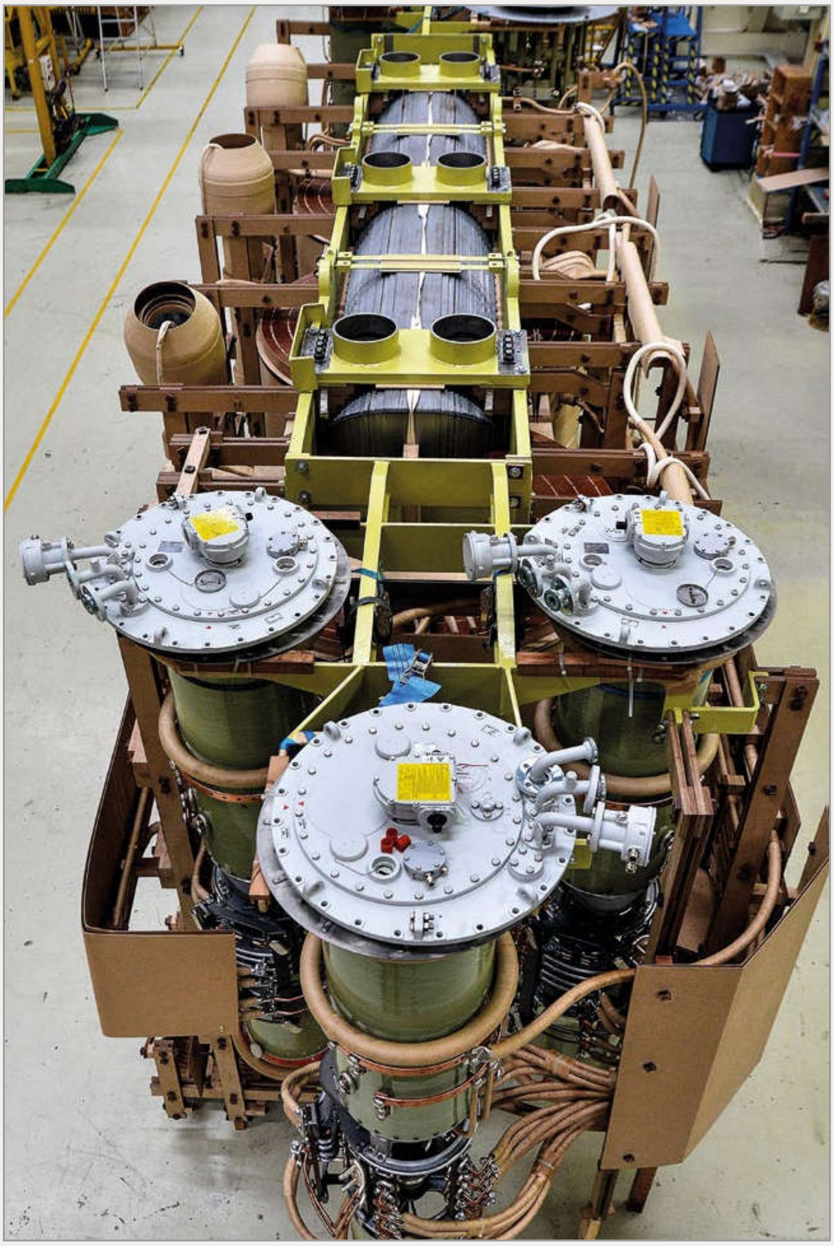


Figure 3. Three-column tap-changers on short side for 161 kV CFVV regulation

Table 1. Insulation levels

	330 kV	161 kV	Neutral (Phase-shifter)
1.2/50 μs lightning impulse (kV peak) (BIL)	1175	650	325
Short duration induced over-voltage 1 min (kV rms) (AC)	540	275	140
Switching impulse (kV peak) (SI)	950	-	-

145 kV, in phase. This is achieved via a voltage regulation winding (F1), as a conventional autotransformer, with the three-column OLTC.

- Phase angle change is on the neutral end of parallel winding and is used to change the sequence of phases the PS winding will connect. The tap-changer used in this position (P) is off-load, but it can be used on-load when the PS winding is not in operation (0°, position 9). By means of this tap changer, phase angle can be set between 120°, -120°, 60° or -60° shifts. It should be noted that the windings will be in-phase when the PS winding is not in operation, regardless of this tap-changer's position. The connection and operating details are explained in Figure 3.

- The phase-shifting is on the neutral end, allowing ±6° variation in 17 positions. Since the PS regulation winding (PS) is on the neutral end, a single-column three-phase OLTC (F2) can be employed. However, the number of turns on both primary and secondary sides is also changed, effecting voltage/turn-ratio of the transformer.

- The variable flux operation (VFVV) caused by the PS expands the transformer's voltage regulation range. With the PS and F windings combined, the transformer has a total of 17x17 tap positions. In all tap positions combined, the transformer can operate between 137 kV to 188 kV on the 161 kV side. The voltage on the 330 kV side is considered constant for this operation.

The PST has three different tap-changers, each with different purposes

3.2 Other technical parameters

The transformers have three-legged cores. No tertiary windings are required. Magnetic flux increase from the flux variation caused by phase-shifting was taken into consideration for the sizing of the core.

The transformer's short circuit impedances vary between 9.5 % and 11 % at 200 MVA base in HV-LV operation. Transformer is ONAN/ONAF cooled.

Insulation levels are outlined in Table 1.

3.3 Design & analysis methods

There were several key considerations in the design of these phase-shifting transformers, which can be summed up in the following points:

- The transformer has 289 tap positions. A standard method of impedance calculation can only provide the solution when the transformer is in-phase. However, maximum and minimum voltages occur when the transformers are in extreme phase shift. Therefore, to calculate impedance voltages and phase-shifting angles, a capacitive calculation software was utilised.

- Voltage distribution on the regulated windings are also of specific importance since the number of positions are so high. Again, the calculation was based on capacitances to determine the risky points on the insulation. These risks were then eliminated by modifications such as placement of edge rings.

- A Finite Element Method software was used to run electrostatic and magnetostatic flux distribution analysis on the transformer. The results of this analysis were used to verify the capability of the insulation.

- In terms of mechanical design, the main problems to be solved were the placement of three different OLTCs and their interconnections. In the final configuration, the main three-column OLTC for

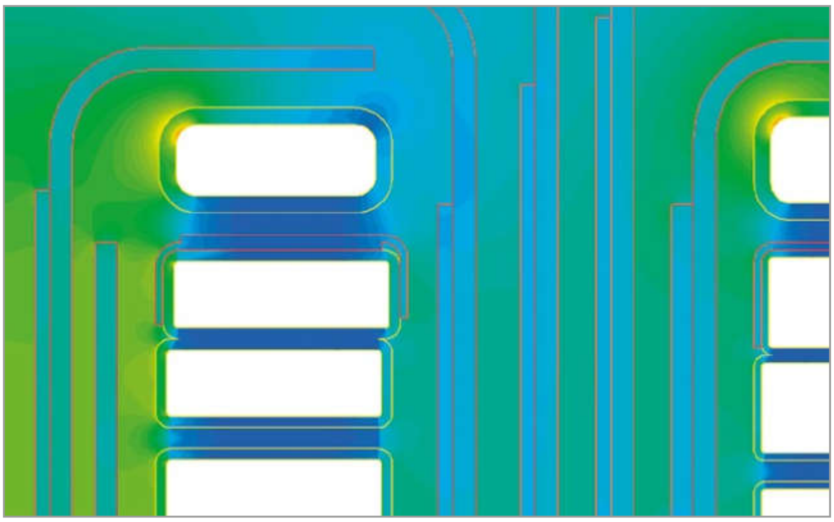


Figure 4. Field distribution image from FEM analysis output

161 kV voltage regulation winding is on one short side of the transformer, while the other two tap-changers for phase shifting are on the other short side.

Even with the added complexity, PSTs are still the most effective solution where such particular needs exist

4. Factory acceptance tests and results

The two transformers were tested at BEST Balıkesir Factory in October 2016. In addition to typical measurements, the following tests were performed on each unit:

- Measurements of voltage ratios and phasor shifts
- Applied voltage, induced voltage withstand, switching impulse and lightning impulse test
- Temperature rise test
- Sound level measurement

Short circuit withstand test was not required based on the previous manufacturer performance.

Out of phase voltage regulation could not be tested in full conformity to the IEC 60076 Standard, but the tests were nevertheless performed to simulate the worst-case condition in all dielectric and thermal withstand tests. The results of the tests are outlined in Table 2.

Transformers passed all tests successfully and design values were confirmed by the test results.

The 200 MVA phase-shifting autotransformer is only slightly larger than a regu-

Table 2. FAT results comparison

			Guarantee	Calculated	FAT	Tolerance
δ Phase-shifting	Max tap, PS=17	±°	4.45	4.44	4.43	±2 %
	Min tap, PS=17		6.33	6.38	6.4	
	PS=9 (any tap)		0	0	0	
	Max tap, PS=1		6.4	6.3	6.37	
	Min tap, PS=1		9.55	9.49	9.43	
Short circuit impedances	Max tap, PS=9	% base 200 MVA	11	10.4	10.29	+5 %, -10 %
	Nom tap, PS=9		10.2	9.9	10	±5 %
	Min tap, PS=9		9.5	9.7	9.53	-5 %, +10 %
	Max tap, PS=1		1	10.6	10.46	+5 %, -10 %
	Nom tap, PS=1		10.6	10.4	10.19	±5 %
	Min tap, PS=1		10.3	10.7	10.62	-5 %, +10 %
Short circuit losses	Max tap, PS=9	kW base 200 MVA	285	284.2	284.6	0 %
	Nom tap, PS=9		304	302.4	301.6	
	Min tap, PS=9		381	380	372.5	
	Max tap, PS=1		326	324.9	323	
	Nom tap, PS=1		366	364.5	345.6	
	Min tap, PS=1		475	473.8	455.7	
No load loss	Nom tap, PS=9	kW, 1.0 Un	58	57.4	52.6	0 %

We can say that a phase-shifting auto-transformer is roughly 30 % heavier than a normal autotransformer of a similar rating

lar autotransformer in terms of its weight and dimensions. Table 3 compares two autotransformers of similar ratings, one manufactured for Ghana network and one used in the Turkish grid. The Turkish utility transformer is VFVV, with only one single-column OLTC on the neutral end, whereas the Ghana transformer has three separate tap-changers of higher voltage levels. This can in part explain the huge difference in oil volume between these two transformers.

Another difference is in the cooling types. The Turkish transformer is OFAF (radiators, fans and pumps) cooled, while the Ghana transformer's cooling unit is ONAF only and requires more radiators. Similarities can be seen on the weight of active parts – even with all extra equipment, Ghana transformer is not much heavier than its Turkish 250 MVA counterpart. Based on this comparison, it can be claimed that a phase-shifting autotransformer is about 30 % heavier than a normal autotransformer of a similar rating.

Conclusions

Two phase-shifting autotransformers of described properties were installed in Ghana in 2016. These transformers not only link the new 330 kV grid to the existing 161 kV, but also allow control of active and reactive power flow. Transmission efficiency will be increased and the burden on the 161 kV lines will be reduced, increasing their stability. Even with the added complexity, this was still the most effective solution for the particular need in Ghana.

Ghana experience is exemplary for many other networks as well. Today, almost all major networks operate with two HV levels, such as the 161 kV and 330 kV networks in Ghana. In some cases even a third, EHV level around 500 kV or 700 kV is added on top of these. At the same time, different country networks are also increasingly being interconnected. To bring them all together, autotransformers are best, and in some cases, the only solution. Phase-shifting autotransformers add to this an even higher functionality, and an increase in efficiency that easily counters the cost increase.

Combining all the mentioned functions in a single tank is not an easy task, however. It requires expert knowledge in transformer design and manufacturing.

Bibliography

[1] IEC 60076 1-0 International Standard, *Power Transformers* 1997-2013

[2] F. Iliceto, F. Marton, C. Darku, *EHV/HV Auto-transformers Within-Phase and In-Quadrature Voltage Regulation. Applications in Ghana*, CIGRE, 2012

[3] Ghana 2014 Electricity Supply Plan, GRIDCO

Table 3. Comparison of two autotransformers of similar rating

	200 MVA Ghana phase-shifting auto-transformer	250 MVA Turkey
Voltage (kV/kV)	330/161	380/158
Frequency (Hz)	50	50
Regulation (± %)	161 kV±8·1.25 %, CFVV	10
Core type	3/0	3/0
Cooling	ONAN/ONAF	ONAN/ONAF/OFAF
Weights		
Complete (T)	265	216
Transportation (T)	158.5	145
Active part (T)	110.5	117
Oil (T)	86.8	48
Dimensions		
Total (LxWxH) (m)	14.2x5.8x9.435	13.75x5.9x8.875
Transport (LxWxH) (m)	11.25x3.95x4.46	8.6x3.15x4.25

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