DEVELOPMENT OF INDIA'S FIRST PHASE SHIFTING TRANSFORMER

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1. INTRODUCTION

This paper focuses on the development of 315 MVA, 400 kV class, 3-phase, Phase Shifting Transformer (PST) by BHEL. PST is an important and a very unique device under Flexible AC Transmission system (FACTS). FACTS devices are versatile equipment for controlling the line flows increasing the loadability of the lines, increase the stability limits with faster response and contain the over voltages on the system. PST is planned for near future in order to meet the new challenges in the grid. This device enables the grid operator to control the loop flows, thus allowing to use the existing system more efficiently, with a higher economic benefit. Installing control devices has the aim to improve the reliability of the system, thus contributing to avoid blackouts.

BHEL is the first manufacturer to have successfully designed, manufactured and tested PST in India. Developed PST consists of shunt unit (315 MVA, 400 kV class, 3-phase) and a series unit (105 MVA, 220 kV class, 3-phase). This PST is to be commissioned at Kothagudem site of APGENCO.

The development of large, high voltage power grids has enabled power consumers to enjoy the benefits of more reliable and efficient service and has allowed generation sources to be, in some cases, located long distances from large load centers. While large interconnected grids strengthen a power system’s reliability, complications can arise with the control of steady-state power flow along certain segments of the system. These complications can be attributed to several factors, including the impedance of parallel paths in the power grid, variation in power generation output, variation in loads and load center phase angles. PST is an important and a very unique device under FACTS which can be used to control the active power flow in a complex power distribution network in a very efficient way & as a result, more power can reach consumers with a minimum impact on the environment. PST works on the principle that the voltage derived from the supply is firstly phase shifted by 90° and then re-applied to it. A phase angle hence developed along the quadrature booster is responsible for affecting the power flow through specified circuits.

The design, manufacturing and testing of a PST poses severe challenges to the designers. The conventional design techniques of 400 kV transformer cannot be simply applied owing to the awesome size and weight of active part and complex Terminal Gear (T.G.). Size of PST depends on the amount of phase shift and number of tap positions in the shunt unit.

The implementation of PST has also several operational consequences. Not only the protection & control of the unit, but also various (external) grid events (lightning strokes, single and multiple phase line faults, auto-reclosure of the circuit breaker) affect the design of the PST. The transformer itself will have an influence on the power flow behavior of the grid, the protection schemes and the automatic system in the S/S. In quadrature boosters the over fluxing and voltage drop depends on the power flow direction.

A reliable PST is the need for reliable and controllable power flow. Many aspects are to be considered and analysed for reliable PST.

These are mainly:
- Selection of number of tappings on shunt unit & its terminal gear.
- Terminal gear for connection between series and shunt units of PST and their insulation co-ordination.
- Methodology for mounting of large number of bushings required for shunt unit and series unit.

The paper details out the principle, constructional details, test results, application & advantages of PST.

2. FLEXIBLE AC TRANSMISSION SYSTEM (FACTS)

The development of FACTS controllers has followed two distinctly different technological approaches. The first group employs reactive impedances with thyristor switches as controlled elements. The second group uses self-commutated static converters as controlled voltage sources.

The first group of controllers viz. Static Var Compensators (SVC), Thyristor Controlled Series Capacitor (TCSC) and Phase Shifter employed conventional thyristors in circuit arrangements which are similar to breaker switched capacitors and reactors and conventional tap changing transformers but these have much faster response and are operated by sophisticated controls. The various methods commonly used in this group are Thyristor Controlled Reactor (TCR) which gives shunt compensation, Thyristor Switched Capacitor (TSC), which gives shunt compensation.
and the Static Var Compensation (SVC), Phase Shifting Transformer (PST) etc.

The second group uses self-commutated static converters as control voltage sources. The methods recently developed in this group are Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC) and the latest addition to this group is the Interline Power Flow Controller (IPFC).

3. PHASE SHIFTING TRANSFORMERS

As seen above Phase Shifting Transformer is an important device under Flexible AC Transmission System (FACTS). It is used to control power flow in an interconnected network. The current distribution between two parallel lines will be in inverse proportion to their impedance. For example in Fig. 1a, the current distribution:

\[ I_1 = \frac{I_{total}}{X_1 - (X_2 + X_3)} \]
\[ I_2 = \frac{I_{total} \cdot X_2}{X_1 - (X_2 + X_3)} \]

However if the system requirement is such that the load should be distributed in a different proportions other than as per Fig. 1a, due to different load carrying capacity of the lines or different load requirements than Phase Shifting Transformer helps to vary the load as desired. Fig. 1b shows the load distribution by use of PST.

4. METHODS TO CONTROL LOAD DISTRIBUTION

4.1 Inphase Control

In this case the control of voltage is in phase with the main winding voltage (Fig. 2a). The voltage is raised/lowered according to the load fluctuations that takes place during operation. This type of voltage support mainly influence on the reactive power flow.

4.2 Quadrature Control

In this case the additional voltage is provided in quadrature with the main winding voltage (Fig. 2b). This regulates the active power flow. In this case no support is given to power system voltage.

4.3 Phase Shift Control

In this case arrangement is provided for controlling the voltage out of phase with the main winding voltage (Fig. 2c). This regulates both the reactive and active power flow. Phase Shift Transformers are also known as quadrature booster transformers.
PST can either be symmetric or quadrature type, single core or dual core type, single tank or dual tank type. The term symmetric means, that under no load condition the voltage magnitude at the load side is equal to the voltage magnitude at the source side, independent from the phase angle. A quadrature type phase shifter is a unit where the boost voltage is perpendicular to the line voltage at one terminal, or to a combination of the line voltages at source and load terminals. Single core, dual core, single tank and dual tank terms are self-explanatory. In most cases a dual core design requires a dual tank design as well, but it is not a necessity.

5.0 FEATURES OF PST DEVELOPED FOR APEGNCO

PST developed by BHEL is for APEGNCO Kothagudem S/s for interconnection between 400 kV & 220 kV lines. The major characteristics were deduced from the results of the load flow calculations (simultaneously were done with and without PST). By system studies it was found that 220 kV lines were overloaded and the 400 kV lines were underutilized. PST was required for power flow from 220 kV to 400 kV line with advance phase shift & from 400 kV to 220 kV in retard phase shift.

The developed PST is a quadrature type, dual core, dual tank design which consists of two transformers called as shunt unit and series unit.

The developed PST is designed for phase shift angle of ±15°. The phase shift angle measurement was demonstrated with interconnection of both the units in actual operating condition and measurement done on all the 35 tap positions.

The rating of the shunt unit is 335 MVA, 400/220/55/33 kV and series unit is 105 MVA, 35/5 kV. The 35 kV of the series unit is connected to the 220 kV of shunt unit and its other end is connected to the 220 kV system. This resulted in providing 6 nos. 220 kV bushings on the tank of series transformer and was a major challenge with regards to spacing etc. The shunt unit consisted of 15 nos. of bushings with 55 nos. of protection CTS. Judicious selection of bushings was done in order to achieve this customer requirement. The 55 kV of series unit is connected to 55 kV of shunt unit through On load tap changer (OLTC).

The interconnection between both the units of PST is shown below.

The tap changer consisted of 35 tap positions per phase i.e. total of 105 leads were routed from OLTC to all three phases of shunt unit. This too posed as a major challenge as routing such large number of leads throughout terminal gear was a herculean task. It was made possible by proper spacing between the leads and by skilled technicians of BHEL. The OLTC support was also strengthened to cater to such huge weight of terminal gear.

Photograph below shows the complex TG of shunt unit.

OLTC chosen is also suitable for frequent operations. Conventional metallic contact tap changers are not suitable for frequent operation, as these contacts are prone to wear and tear due to continuous tap changing operations. To overcome above, other static type of vacuum type of OLTC is required, which is suitable for unlimited (life long) operation.

The specification of the developed prototype shunt and series transformers are as follows:

**Shunt Unit**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>315/315/105 MVA for HV/LV/Control/LV</td>
</tr>
<tr>
<td>Voltage ratio</td>
<td>400/220/55/33 kV</td>
</tr>
<tr>
<td>Vector group</td>
<td>YynynD11</td>
</tr>
<tr>
<td>Tappings</td>
<td>35 steps, 2.24 kV each</td>
</tr>
<tr>
<td>% Impedance (HV-LV) (guar.)</td>
<td>12.5% ± 1.5% Tol</td>
</tr>
<tr>
<td>Type of cooling</td>
<td>ONAN/ONAN</td>
</tr>
<tr>
<td>Oil rise (G)</td>
<td>75°C</td>
</tr>
<tr>
<td>Wind. rise (G)</td>
<td>55°C</td>
</tr>
</tbody>
</table>

Photograph below shows the Shunt unit of PST under test at Bhepal works.

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**Image**

CONNECTION DIAGRAM OF SHUNT & SERIES UNIT OF PST

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**Figure**

Photograph below shows the complex TG of shunt unit.
6. SPECIAL FEATURES OF PST:

6.1 Bushing Terminals:
6.1.1 15 nos. bushing terminals are required for shunt unit, 12 bushings for line voltage and 1 no. each for neutral terminals of Y-connected windings.

6.1.2 9 nos. bushing terminals are required for series unit, out of which 6 bushings are for primary line voltage and other 3 bushings are for secondary winding.

6.1.3 For higher system voltage like 245 kV and 420 kV, large clearance is required between phase to phase and accommodation of 6 high voltage bushings (245 kV) for series unit on tank cover requires special techniques.

6.1.4 Line bushings of shunt & series units are to be provided in such a manner that during over head interconnection of shunt & series unit, there shall be no cross-connection.

6.1.5 Owing to its unique design for shunt unit, i.e., having 4 independent windings, customer requirement of large number of tap positions results in large size & weight of active part. Apart from dielectric considerations, mechanical considerations are equally important for such type of transformers. These considerations result in large volume of tank and hence large size trailers are required for transportation upto site.

Photograph below shows the Shunt unit of PST loaded on trailer for transportation upto site.

6.2 Vacuum Tap Changer

6.2.1 Vacuum tap changer are very effective for smooth & trouble free phase shifting operations.

7. APPLICATION & ADVANTAGES

Phase Shifting Transformers can be used to achieve following advantages:

7.1 Desired distribution of power flow in parallel lines and heavily loaded networks.

7.2 Avoidance/reduction of circulating currents

7.3 Minimisation of losses in parallel transmission corridors with different voltage levels and/or different lengths.

7.4 Energy transmission, redistribution to higher voltage levels, which are often under utilized.
7.5 Energy transfer over specified contract paths without with minimal loading of third party networks.
7.6 Higher reliability of power supply plus improved distribution of power flow.
7.7 Highly robust FACTS components achieved in combination with reactors and capacitors.

8. CONCLUSION
The successful development of the phase shifting transformer shall give a great impetus to the power scenario of the country.

Acknowledgements - The authors wish to place on record all the help rendered by the members of Transformer division Bhopal, EDN Bangalore, Industry Sector and Corp. R&D. The authors are thankful to BHEL management for giving approval to present this paper.

REFERENCES
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THE GREATEST THING IN THE WORLD IS NOT SO MUCH WHERE WE ARE BUT IN WHAT DIRECTION WE ARE MOVING