Solid State Transformer Parallel Operation with a Tap Changing Line Frequency Transformer

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Abstract—Increase in load demand require upgrade of distribution transformers and significant investments. An alternative to a complete overhaul of the distribution transformer is to operate a solid state transformer in parallel with the line frequency transformer. This allows functionality to either share the load or accommodate overload conditions. In addition, other options for superior distribution system voltage control may be present. This paper focuses on the parallel operation and control strategy for a 33 kV / 415 V, 200 kVA distribution transformer with a 200 kVA parallel solid state transformer. Two control strategies, namely parallel load sharing operation and overload accommodation are investigated. Simulation results are presented for the parallel operation of a SST with a LFT and the effectiveness of the two strategies are discussed.

Index Terms—Solid state transformer, distribution system, voltage control, parallel operation, overload accommodation

I. INTRODUCTION

The consumer density and consumer behavior varies rapidly in distribution systems over time and as a result, the load may significantly increase from its rated loading conditions during the normal lifetime of a transformer. In addition, such changes leads to low load factor resulting in high peak loads [1]. This leads to frequent overloaded operation of transformers and it is found that distribution transformer failure is mainly due to overloading [2]. Prolonged overloading of a transformer leads to thermal degradation of the winding [2]–[8] and reduction in lifetime and reliability of the system [9], [10]. Typical solution is the replacement of an existing distribution transformer with a higher rated power transformer and may incur a significant cost. Such a solution may lead to lower utilization factor for the transformer.

An alternatively solution is to supplement the exiting line frequency transformer (LFT) with a paralleled solid state transformer (SST). This alternative option provides extended lifetime of the distribution transformer by eliminating overloaded operation that occur during peak load conditions. Furthermore, reactive power support can also be utilized to maintain voltage regulation on the distribution side. Recent smart grid concepts are also facilitated by the power electronic energy conversion stage of the SST and hence opens up a multitude of energy management options with electronic control. This paper investigates the parallel operation of a solid state transformer (SST) with a tap changing line frequency transformer (LFT). Two basic control and operation strategies, namely parallel load sharing operation and overload accommodation of the SST are developed in this paper.

II. MATHEMATICAL MODELLING

A. Operation of the Solid State transformer and equivalent model

The established three stage solid stage transformer technology [11], [12] consist of a front-end multilevel rectifier stage, multiple dual active bridge (DAB) energy conversion and isolation stages and thereafter a common DC-link and inverter stage. The solid state transformer topology considered in this study is shown in Fig 1. The front end consists of a 7 level cascaded H-bridge (CHB) structure. Each IGBT module is rated at 6.5 kV. The three phases consists of a 21 such modules. The front end is connected with the 33 kV medium voltage distribution transformer primary terminals. The voltage balancing is provided by the control of the 7-level CHB structure. The DAB is controlled by phase shifting control. The low voltage side of the SST consists of three-leg 3-phase inverter as shown in Fig 1. This SST is interfaced in parallel with a tap changing LFT as shown in Fig 3. The LFT considered in this study is a 33 kV/415 V tap changing transformer rated at 200 kVA.

The control of the solid state transformer involves current
control of both the grid side inverter and the front end rectifier [11]. The front end rectifier and DAB DC-link voltages are controlled by the inner current control loops. The voltage balancing between the DAB DC-link voltages is controlled by the active rectifier switching control [11]. The DAB control regulates the low voltage side DC-link voltage. The low voltage grid-side inverter current control operation is fed with the required power commands generated by the load sharing control strategy. The detailed control system of the SST is not discussed here as it is established in research presented in [11], [13]–[18]. For the analysis of the parallel operation of a SST and LFT, the current control action on the low voltage grid side inverter is represented by a current injection denoted in d-q frame. Given the required active and reactive power injection into the grid by $p_g$ and $q_g$ respectively, the relationship between the d-q voltages and currents is given by:

$$
\begin{bmatrix}
    p_g \\
    q_g
\end{bmatrix} =
\begin{bmatrix}
    v_{gd} & v_{gq} \\
    -v_{gq} & v_{gd}
\end{bmatrix}
\begin{bmatrix}
    i_{gd} \\
    i_{gq}
\end{bmatrix}
$$

(1)

The per-unit impedance of the high voltage side tap changing winding is calculated by its inverse transformation:

$$
\begin{bmatrix}
    i_{gd} \\
    i_{gq}
\end{bmatrix} =
\frac{1}{v_{gd}^2 + v_{gq}^2}
\begin{bmatrix}
    v_{gd} & v_{gq} \\
    -v_{gq} & v_{gd}
\end{bmatrix}
\begin{bmatrix}
    p_g \\
    q_g
\end{bmatrix}
$$

(2)

Similarly the front end cascaded H-bridge rectifier is also modelled as a controlled current source. The control strategy for the parallel operation of the SST and LFT operates at lower bandwidth than the inner current control loops, and has a natural frequency below the switching frequency. Hence the high frequency dynamics of the active rectifier stage DC-link voltage, the DAB power transfer and the low voltage side DC-link voltage are considered as a first order lag represented by a delay of real power transfer from the commanded $p_g^*$ to the actual power delivered from the HV-side:

$$
p_{g, hv} = \frac{1}{\tau s + 1} p_{g, lv}^*
$$

(3)

$$
p_{g, lv} = p_{g, lv}^*
$$

(4)

where $\tau$ represents the effective time constant of the combined inner current control and outer voltage control loops. $p_{g, hv}$ and $p_{g, lv}$ are the real power of the HV side and the LV side respectively.

B. Operation of the Tap Changing Line Frequency transformer and its equivalent model

During normal operation of the distribution transformer considered in this study, the voltage regulation is achieved mainly by the tap the changing operation. Fig 2 shows the winding arrangement of the Dy11 transformer considered in this study. The tap changing operation consists of 8 taps and a changeover tap thereby providing 17 tap positions.

The high voltage side delta connected winding consists the main section with $Z_{D, pu}$ per-unit impedance and a tap changing winding with a full per-unit impedance of $Z_{T, pu}$. The low voltage side star connected winding per-unit impedance as $Z_{Y, pu}$. The transformer primary and secondary rated voltages are represented by the nominal values $V_{HV, nom}$ and $V_{LV, nom}$.

The required reference d-q current commands are hence calculated by its inverse transformation:

$$
\begin{bmatrix}
    i_{gd} \\
    i_{gq}
\end{bmatrix} =
\frac{1}{v_{gd}^2 + v_{gq}^2}
\begin{bmatrix}
    v_{gd} & v_{gq} \\
    -v_{gq} & v_{gd}
\end{bmatrix}
\begin{bmatrix}
    i_{gd} \\
    i_{gq}
\end{bmatrix}
$$

(2)

$$
\begin{bmatrix}
    p_g \\
    q_g
\end{bmatrix} =
\begin{bmatrix}
    v_{gd} & v_{gq} \\
    -v_{gq} & v_{gd}
\end{bmatrix}
\begin{bmatrix}
    i_{gd} \\
    i_{gq}
\end{bmatrix}
$$

(1)

The voltage-step per-tap is represented by the parameter $\Delta U$ and considering a high voltage side base voltage at the nominal value of $V_{HV, nom}$, the per-unit voltage-step per-tap is denoted by $\Delta U_{pu}$. Given the low voltage side of the transformer is at a fixed winding tap, the ratio between the high voltage side and the low voltage side is given by:

$$
\frac{V_{HV}}{V_{LV}} = \frac{V_{HV, nom} (1 + \Delta U_{pu} T)}{V_{LV, nom}}
$$

(5)

The tap position variable $T$ may vary between $-8 \leq T \leq +8$. Depending on the $T$ value, the tap position as well as the changeover tap position is automatically adjusted. $T = 0$ represents the nominal position. Provided that the low voltage side base is taken as $V_{LV, nom}$, the high voltage side base is then given by:

$$
V_{HV, base} = V_{HV, nom} (1 + \Delta U_{pu} T)
$$

(6)

The winding reactance of the transformer high voltage side main winding and the tap changing winding and the low voltage side winding are represented by $X_{D, pu}$, $X_{T, pu}$ and $X_{Y, pu}$ where the $X_{T, pu}$ is divided into $N$ taps positions. These per-unit values are represented with the impedance base considering the nominal voltages of the primary and secondary sides as the base values. Due to the tap changing operation, the high voltage side voltage base changes and hence the high voltage side impedance base changes as a function of tap position. For a common power base $S_{base}$, the high voltage side impedance base is given by:

$$
Z_{HV, base} = \frac{V_{HV, base}^2}{S_{base}} (1 + \Delta U_{pu} T)^2
$$

(7)

where the nominal Impedance base is given by:

$$
Z_{HV, nom} = \frac{V_{HV, base}^2}{S_{base}}
$$

(8)

Hence the new per-unit impedance of the high voltage side winding is given by:

$$
Z_{D, new, pu} = Z_{D, pu} Z_{HV, nom} \frac{1 + \Delta U_{pu} T}{1 + \Delta U_{pu} T}
$$

(9)

The per-unit impedance of the high voltage side tap changing portion is given by:

$$
Z_{T, new, pu} = \frac{(\Delta U_{pu} T)^2 Z_{T, pu} Z_{HV, nom}}{Z_{HV, base}}
$$

(10)

Substitution of (7) and (8) in (10) yields:

$$
Z_{T, new, pu} = \left( \frac{\Delta U_{pu} T}{1 + \Delta U_{pu} T} \right)^2 Z_{T, pu}
$$

(11)

Hence the total per unit transformer impedance is given by the sum of the primary high voltage winding impedance and the secondary low voltage winding impedance:

$$
Z_{T, pu} = \frac{Z_{D, pu} + (\Delta U_{pu} T)^2 Z_{T, pu}}{(1 + \Delta U_{pu} T)^2} + Z_{Y, pu}
$$

(12)
\[
P_{pu} = V_{HV,pu,nom}V_{LV,pu,nom} \frac{(1 + \Delta U_{pu}T)}{X_{D,pu} + (\Delta U_{pu}T)^2 X_{T,pu} + (1 + \Delta U_{pu}T)^2 X_{Y,pu}} \sin \delta
\]

\[
Q_{pu} = \frac{V_{HV,pu,nom}V_{LV,pu,nom}(1 + \Delta U_{pu}T)}{X_{D,pu} + (\Delta U_{pu}T)^2 X_{T,pu} + (1 + \Delta U_{pu}T)^2 X_{Y,pu}} \cos \delta - \frac{V_{LV,pu,nom}^2(1 + \Delta U_{pu}T)^2}{X_{T,pu} (1 + \Delta U_{pu}T)}
\]

Fig. 2: Three-phase Dy11 tap changing transformer winding arrangement

The high voltage side and the low voltage side per-unit voltage given by:

\[
V_{HV,pu} = \frac{V_{HV}}{V_{HV,nom}} = \frac{V_{HV}}{V_{HV,nom} (1 + \Delta U_{pu}T)}
\]

and

\[
V_{LV,pu} = \frac{V_{LV}}{V_{LV,nom}}
\]

Neglecting the resistances, the real power transfer across the transformer can be written as:

\[
P_{pu} = \frac{V_{HV}V_{LV}}{V_{HV,nom}V_{LV,nom} (1 + \Delta U_{pu}T)} X_{tf,pu} \sin \delta
\]

The reactive power transfer can be written as:

\[
Q_{pu} = \frac{V_{HV}V_{LV}}{V_{HV,nom}V_{LV,nom} X_{tf,pu} (1 + \Delta U_{pu}T)} \cos \delta - \frac{V_{LV,pu,nom}^2}{X_{tf,pu}}
\]

Voltage values with the nominal per-unit values can be replaced with:

\[
V_{LV,pu,nom} = \frac{V_{LV}}{V_{LV,nom}} \quad \text{and} \quad V_{HV,pu,nom} = \frac{V_{HV}}{V_{HV,nom}}
\]

which result in:

\[
P_{pu} = \frac{V_{HV,pu,nom}V_{LV,pu,nom}}{(1 + \Delta U_{pu}T)} X_{tf,pu} \sin \delta
\]

and

\[
Q_{pu} = \frac{V_{HV,pu,nom}V_{LV,pu,nom}}{X_{tf,pu} (1 + \Delta U_{pu}T)} \cos \delta - \frac{V_{LV,pu,nom}^2}{X_{tf,pu}}
\]

Equations (20) and (21) describes the LFT power transfer for a given tap position \( T \) and is used in the overload accommodation mode real power and reactive power control of the SST presented in the following section.

III. PARALLEL OPERATION OF THE SST AND THE LFT

Two modes of parallel operation of the SST and the LFT transformer are investigated in this paper and are discussed in this section:

A. Load sharing mode operation:

In this mode of operation, the SST transformer is set to share a predefined fraction of the load demand. This basically allows increase in the overall capacity of the SST-LFT combination. Given the load sharing fraction as \( \lambda \) and the total real and reactive power demanded by the distribution system \( P_{load} \) and \( Q_{load} \), the control of the SST enables sharing of the load according to:

\[
P_{SST,pu}^* = \frac{1}{\tau_{ls}s + 1} \lambda P_{LFT,pu}^*
\]

\[
Q_{SST,pu} = \frac{1}{\tau_{ls}s + 1} \lambda Q_{LFT,pu}
\]

where \( \tau_{ls} \) is the load sharing time constant. At steady-state, the total load delivered by the SST-LFT combination is given by:

\[
P_{load} = (1 + \lambda) P_{LFT,pu} \quad \text{and} \quad Q_{load} = (1 + \lambda) Q_{LFT,pu}
\]

This control strategy can be implemented by estimation of the LFT transformer power transfer via (20) and (21) and commanding the SST to contribute a portion of power according to (22). The low voltage grid side inverter commands are calculated according to (2). Alternatively, the transformer power can also be calculated by:

\[
P_{LFT,pu} = \text{Re} \{ V_{B3}I_{I,f,lv}^* \} \quad \text{and} \quad Q_{LFT,pu} = \text{Im} \{ V_{B3}I_{I,f,lv}^* \}
\]

B. Overload accommodation mode operation:

In this mode of operation, the SST is active only if the total load demand is in excess of a predefined value. With the SST in parallel, the control strategy curtails the transformer power and transfers this difference through the SST. This control strategy is more complicated than the load sharing control.
strategy and requires calculation of the nominal transformer real power and reactive power transfer for a given load scenario.

The power transfer at bus #3 can be calculated by:

\[ P_{B3} = \text{Re}\{V_{B3}I_{B3}^*\} \quad (26) \]
\[ Q_{B3} = \text{Im}\{V_{B3}I_{B3}^*\} \quad (27) \]
\[ S_{B3} = \sqrt{P_{B3}^2 + Q_{B3}^2} \quad (28) \]

If \( S_{B3} \geq S_{\text{max}} \), the SST is activated. In order to maintain the LFT apparent power at a maximum of \( S_{\text{max}} \) at a low voltage side voltage reference of \( V_{B3}^* \), the voltage phase angle difference between buses #2 and #3 is required to be maintained at a reference value \( \delta^* \). Manipulation of (15) and (16) yields a relationship between these reference values as given in (29).

Hence, the reference phase angle \( \delta^* \) can be calculated by:

\[
\delta^* = \cos^{-1}\left\{ \left(\frac{V_{HV,pu}V_{LV,pu}^*}{X_{t,f,pu}}\right)^2 + \left(V_{LV,pu}^*\right)^4 - S_{\text{max}}^2X_{t,f,pu}^2 \right\}^{1/2} \frac{2V_{HV,pu}}{S_{\text{max}}^3} \quad (30)
\]

where \( V_{HV,pu} \) and \( X_{t,f,pu} \) are given by (13) and (12). The corresponding LFT real power and reactive power reference values can be calculated from (20) and (21) by substitution of \( V_{LV,pu} = V_{LV,pu}^* \) and \( \delta = \delta^* \). The transformer real and reactive power transfer is forced to this value by injection of the corresponding difference by the SST by the control action of the form:

\[ P_{SST}^* = \int \{k_1(P_{LFT}^* - P_{LFT}) - k_2P_{SST}^*\} dt \quad (31) \]
\[ Q_{SST}^* = \int \{k_1(Q_{LFT}^* - Q_{LFT}) - k_2Q_{SST}^*\} dt \quad (32) \]

where the gains \( k_1 \) and \( k_2 \) are given by:

\[
\begin{cases} 
  k_1 = -1 & \text{and} & k_2 = 0 & \text{if} & S_{B3} > S_{\text{max}} \\
  k_1 = 0 & \text{and} & k_2 = 1 & \text{if} & S_{B3} < S_{\text{max}} 
\end{cases} \quad (33)
\]

The gain \( k_1 \) acts as an integral action on the power difference between the LFT reference and the actual LFT power. The gain \( k_2 \) act as an attenuation coefficient which imposes a gradual decay of the power transfer through the SST upon reduction of the load demand \( S_{B3} \) to a value below the preset value of \( S_{\text{max}} \). The following section presents simulation results on the both the above two control modes of SST operation.

IV. SIMULATION RESULTS

The SST and the LFT equivalent models are implemented in software and the two control strategies outlined earlier have been simulated. The SST-LFT combination is implemented in 33 kV transmission feeder on the high voltage side and the 415 V distribution line on the low voltage line as shown in Fig 3. The end of the distribution line is connected with a variable load. Table I outlines the parameters associated with the LFT, SST, feeder and the distribution line adopted in this study.

The load consist of three resistive/inductive loads. In each simulation, a resistive/inductive load consists of a 1.72 \( \Omega \) resistance in parallel with a 3.44 \( \Omega \) reactance such that the power consumed by the load at 1 pu voltage is 100 kW real power and 50 kVAR lagging reactive power. Fig 4 shows the simulation results under the load condition simulated. The simulation is performed for a 200 s period. At \( t = 0 \) s the system operated under no-load and the first resistive/inductive load is switched on at \( t = 15 \) s and represents a light-load condition. The second resistive/inductive load is switched on at \( t = 45 \) s and represents a medium load condition. The third resistive/inductive load is switched on at \( t = 75 \) s and represents an high-load/overload condition. Thereafter the third load, second load and the first load are sequentially disconnected at \( t = 105 \) s, \( t = 135 \) s and \( t = 165 \) s and thereafter operated under no-load.

Fig 4 shows the simulation results for the two control strategies outlined earlier. In addition to the two control strategies, Fig 4 also shows the LFT normal operation without the SST for comparison purposes. Fig 4 (a) and (b) show the low voltage side terminal voltage and the load terminal voltage. Fig 4 (c) shows the tap position under each of the operation modes. Fig 4 (d), (e) and (f) shows the LFT real power transfer, reactive power transfer and the associated
Fig. 4: Simulation results for normal LFT operation, SST parallel operation in load sharing mode and SST parallel operation in overload accommodation mode: (a) Low voltage side terminal voltage $V_{BS}$, (b) Load terminal voltage $V_{B4}$, (c) Tap position, (d) LFT Real power transfer, (e) LFT Reactive power transfer, (f) LFT Apparent power transfer, (g) SST Real power transfer and (h) SST Reactive power transfer.

TABLE I: Parameters of the SST and LFT system considered in this study

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<thead>
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<th>LFT parameters</th>
<th>value</th>
<th>SST parameters</th>
<th>value</th>
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<tr>
<td>Rated power [kVA]</td>
<td>200</td>
<td>Rated power [kVA]</td>
<td>200</td>
</tr>
<tr>
<td>Rated voltage HV side [kV]</td>
<td>33</td>
<td>Rated voltage HV side [kV]</td>
<td>33</td>
</tr>
<tr>
<td>Rated voltage LV side [V]</td>
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<td>Rated voltage LV side [V]</td>
<td>415</td>
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<tr>
<td>Voltage step [pu]</td>
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<td>7</td>
</tr>
<tr>
<td>Primary resistance [pu]</td>
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<td>Rated voltage on the CHB DC-link [V]</td>
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<td>Primary reactance [pu]</td>
<td>9%</td>
<td>IGBT rated voltage [V]</td>
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<td>Secondary reactance [pu]</td>
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<td>Tap changing winding resistance [pu]</td>
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<td>DAB switching frequency [kHz]</td>
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<td>Dead band voltage [pu]</td>
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<table>
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<td>Feeder length [km]</td>
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apparent power respectively. Fig 4 (g) and (h) shows the SST real power and reactive power transfer respectively.

It can be seen from 4 (g) and (h) that the SST real power and reactive power transfer is not present during normal operation of the LFT. Hence, during the high load and medium load conditions the tap position is at its minimum (-8 position at highest tap) and as a result the voltage regulation fails to achieve its reference value of 1.1 pu as shown by the dark line in Fig 4 (a). The load terminal voltage is also shown by the dark line in Fig 4 (b) and has the lowest value during this
The waveforms during the load sharing mode is shown by the green dotted lines. As explained earlier, the load sharing mode forces the SST to inject a fraction of the total power demand, thereby reducing the loading on the LFT. In this simulation, the load sharing parameter \( \lambda \) is selected as \( \lambda = \frac{1}{4} \). Hence as seen by comparing the real power from Fig 4 (d) and (g), and reactive power from Fig 4 (e) and (h) that the SST shares \( \frac{1}{4} \) of the power of the LFT under all loading conditions. As a result of this extra capacity, the voltage regulation improves and the transformer terminal voltage is kept at the reference value of 1.1 pu nearly all the load conditions.

The waveforms during the overload accommodation mode is shown by the red lines. In this mode, the SST is activated only if the total power demand exceed a present maximum apparent power value, in this case 175 kVA. If the total apparent power demand exceeds 175 kVA, the LFT power is regulated at the 175 kVA value while the remainder is injected by the SST. The injected real power and reactive power by the SST can be seen from Fig 4 (g) and (h) respectively. It can be seen that the overload accommodation mode is active approximately from \( t = 48 \text{ s} \) to \( t = 130 \text{ s} \). The LFT apparent power shown in Fig 4 (f) red line demonstrates the regulation of the LFT power to 175 kVA during this period. This is achieved by individual regulation of the real power and reactive power to a calculated reference value shown by the dark dotted line in Fig 4 (d) and (d). It can be seen that the red line in these figures converge to the dark dotted line hence achieving the LFT apparent power regulation. Fig 4 (a) demonstrates superior voltage regulation in this mode of operation as the voltage converges to the reference 1.1 pu rapidly during high load conditions due to the SST action. Furthermore, the number of tap changes during this period is also reduced and can be considered as an advantage.

V. CONCLUSION

The parallel operation of a tap changing LFT and a SST has been investigated. Two control strategies, namely load sharing mode and overload accommodation mode has been outlined. The mathematical modelling and control background for these two control strategies have been presented. A 33 kV to 415 V transformer rated at 200 kVA has been simulated in parallel with a 200 kVA SST. The two proposed control strategies have been analysed with simulation results. It has been shown that the load sharing mode operation is successful and shares the load between the LFT and the SST at the predefined fraction for all the load conditions. The load sharing mode operation hence reduces the transformer overload and improves the voltage regulation. The overload accommodation mode is also shown to be successful and regulates the transformer power at a predefined apparent power value during overloaded operation. Simulation results show that the proposed control strategy successfully forces the SST to inject the remainder of the power demand and avoid overloading the transformer.

This strategy is also shown to improve the voltage regulation of the SST-LFT combination.

REFERENCES


