Abstract—Since capacity of short circuit (S.C.) laboratory depends upon effective impedance of testing transformer and line connecting to the test equipment, which is designed to the optimal level while developing the S.C. Lab but still its fault level is lower. To test higher rating of transformer, a high testing fault level is required. Paralleling of S.C. testing transformer is the only effective way to reduce the effective impedance and increase fault level of the S.C. Lab. Percentage impedance of the conventional power transformer are found to be rated at 7 to 8%, while in case of S.C. testing transformer. This is much lower. S.C. testing transformer is specially designed transformer due to above aspect. This paper targets to provide solution for enhancing S.C. capacity of testing laboratory by connecting another transformer of similar capacity parallel to existing one and to deal with the phenomena of sympathetic inrush current, circulating current etc. This paper discusses simulation in ETAP & PSCAD for fault current estimation for the single S.C. testing transformer and after paralleling of two transformers. Simulation results and mathematical results both are observed identical

Keywords—Short circuit capacity, Parallel operation of transformer, Sympathetic inrush current, Circulating current.

I. INTRODUCTION

Short circuit testing laboratory seeks source maximum short circuit power which is generally in two ways 1) Self generating short circuit laboratory (having inbuilt generating facility) and 2) On-line (grid connected) short circuit source which is obtained power from power system network. Requirement of short circuit source power is generally eight to ten times of test object short circuit power. In online short circuit laboratory only way to enhance the fault level this is paralleling of transformer. Transformers, can be operated in parallel by connecting similarly marked terminals provided that their ratios, voltages, angular displacement, resistances, reactance’s, and ground connections are such as to permit parallel operation The difference in the no-load terminal voltages of the transformers causes a circulating current to flow between the transformers when paralleled irrespective of load. The circulating current is limited by the overall impedance of the circuit, which is usually the sum of the impedances of the transformers that are operating in parallel. The circulating current adds up, considering phasor relationships, to the load current to establish the total current in the transformer. As a result, the short circuit testing capacity of the transformer is reduced by the circulating current when the transformers are paralleled. For voltage ratios with a deviation of less than the 0.5%, as required by the IEEE standards, the circulating current between paralleled transformers is usually insignificant. Transformer is a main component of power system. Generally, the paralleling of lower-power transformers offers a number of advantages over a single high power transformer. The advantages include improved reliability, higher efficiency, redundancy implementation, expandability of output power, and ease of maintenance. In fact, the paralleling of conventional transformers has been widely used in power system.

Failure of transformers due to short circuits is a major concern for power utilities and manufacturers. An inadequate short-circuit strength may lead to a mechanical collapse of windings and deformation or damage to the clamping structure. The short circuit design is one of the most important and challenging aspects of transformer design. Due to this reason short circuit testing transformer is a special design transformer and its impedance is very low. To test higher rating of transformer, a high fault level is required. This is being explored in this paper by putting another transformer in parallel to the existing transformer; Due to this short circuit fault level will be increase. Paralleling of transformers are required special protection scheme which is related to inrush and sympathetic inrush current, circulating current. Test object inrush current interferes in short circuit current, so control switching circuitry is required. Enhancement of fault level & respective upgrade in protection schemes are simulated, analyzed & discussed in succeeding section.

II. MATHEMATICAL FORMULATION

A. Fault Level Calculation for Existing System

![Fig. Single line diagram for existing system](image)

1) System impedance, $Z_{s, F} = \frac{kV^2}{MVA_{sc}}$
\[
Z_{sp} = \frac{220^2}{5056} = 9.5728 \text{ Ohm on 220 kV side}
\]

2) Reactance Referred To 33 kV Side
\[
Z_{ss} = Z_{sp} \times n^2 = 9.5728 \times \frac{33^2}{220^2} = 0.21539 \text{ Ohm} \ldots \ldots \ldots \ldots A
\]

3) Power transformer Z power = 80 MVA
\[
Z = \frac{\%Z \times kV^2}{100 \times \text{MVA}}
\]

4) Z power referred to 33 kV side
\[
Z = \frac{8 \times 33^2}{100 \times 80} = 1.089 \text{ Ohm} \ldots \ldots \ldots \ldots B
\]

5) Minimum load impedance Z load = 0.08 Ohm \ldots \ldots \ldots \ldots C

6) Total Z on 33 kV = A + B + C
\[
= 0.2154 + 1.089 + 0.08 = 1.3844 \text{ Ohm}
\]

7) Fault MVA on 33 kV
\[
kV^2 = \frac{33^2}{1.3844} = 786.629 \text{ MVA}
\]

(Source short circuit power)

8) Source short circuit power
\[
= 8.82 \times \text{short circuit power of transformer under test}
\]

Therefore max short circuit power of transformer under test
\[
= \frac{\text{Source short circuit power}}{8.82} = 89.187 \text{ MVA}
\]

Using existing system we can perform maximum 6.37 MVA (%Z=7.15) transformers. It’s depends upon impedance of test object which is shown in table II

**Fault Level Calculation for Parallel Transformer**

![Fig.2 Fault Level Calculation for Parallel Transformer](image)

All mathematical formula for parallel operation is same except two calculations which are written following.

1) Two transformers connected in parallel then effective impedance
\[
= \left[ \frac{1}{Z_1} + \frac{1}{Z_2} \right]^{-1}
\]

2) \[ MVA_{eff} = MVA_1 + MVA_2 \]

All other result are written in table I and II

**Comparison between existing and proposed system parameters**

<table>
<thead>
<tr>
<th>S/N</th>
<th>Parameters</th>
<th>Existing Sys.</th>
<th>Proposed Sys.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Input Fault Level (MVA)</td>
<td>5056 MVA</td>
<td>5056 MVA</td>
</tr>
<tr>
<td>2</td>
<td>Sys. Impedance on 220 kV side</td>
<td>9.5728 ohm</td>
<td>9.5728 ohm</td>
</tr>
<tr>
<td>3</td>
<td>Sys. Imp. Referred to 33 kV side</td>
<td>0.21539 ohm</td>
<td>0.21539 ohm</td>
</tr>
<tr>
<td>4</td>
<td>Z power Referred to 33 kV side</td>
<td>1.089 ohm</td>
<td>0.5445 ohm</td>
</tr>
<tr>
<td>5</td>
<td>Minimum load impedance</td>
<td>0.08 ohm</td>
<td>0.08 ohm</td>
</tr>
<tr>
<td>6</td>
<td>Total Z on 33 kV</td>
<td>1.3844 ohm</td>
<td>0.8399 ohm</td>
</tr>
<tr>
<td>7</td>
<td>Fault Level on 33 kV side</td>
<td>786.629 MVA</td>
<td>1296.6 MVA</td>
</tr>
<tr>
<td>8</td>
<td>Max. S.C. Power of Test Object</td>
<td>89.187 MVA</td>
<td>147.007 MVA</td>
</tr>
</tbody>
</table>

Calculation for maximum MVA of transformer which can be tested using existing and proposed system which is written in table II

1) Short circuit power of transformer under test

\[
= \frac{\text{MVA rating of test object} \times \% \text{ Impedance of test object}}{100}
\]

2) Maximum MVA of transformer which can be tested for different impedances

\[
= \frac{\text{MVAt}_{\text{max}} \times \%Z_1}{100}
\]

Where:-
$$\text{MVAt}_{sc} \Rightarrow \text{Maximum short circuit power of transformer under test}$$

$$%Z_t \Rightarrow \% \text{Impedance of transformer under test}$$

### TABLE II

<table>
<thead>
<tr>
<th>S/N</th>
<th>% Imp. of Trans.</th>
<th>MVA that can be Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Existing Sys.</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>3.6675</td>
</tr>
<tr>
<td>2</td>
<td>4.5</td>
<td>4.0134</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>4.4594</td>
</tr>
<tr>
<td>4</td>
<td>6.25</td>
<td>5.5742</td>
</tr>
<tr>
<td>5</td>
<td>7.15</td>
<td>6.3769</td>
</tr>
<tr>
<td>6</td>
<td>8.15</td>
<td>7.2687</td>
</tr>
<tr>
<td>7</td>
<td>8.35</td>
<td>7.4471</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>8.9187</td>
</tr>
<tr>
<td>9</td>
<td>12.5</td>
<td>11.1464</td>
</tr>
</tbody>
</table>

According to this table we can perform 10.5 MVA (%Z=7.15) transformers using parallel operation. It is also depends upon % impedance of transformer which is 7 to 8% generally.

### III. PROTECTION OF PARALLELED TRANSFORMER

There is so many precautions are required for paralleling of transformer. Some of the typical problem described following.

1. Inrush and sympathetic inrush current protection
2. Circulating current minimization and protection

#### A. Inrush and sympathetic inrush current protection

Sympathetic inrush current phenomenon occurs when a transformer is switched on in a power system network containing other transformers which are already energized, incoming transformer realizes inrush current and already energized transformer realize sympathetic inrush current. A number of factors affect the magnitude and duration of the sympathetic inrush and inrush current, such as air core reactance, system fault level, point on wave switching, residual flux density, number of banked transformers, transformer design and rating and load conditions. In this case sympathetic inrush current impact is very low and inrush current in upcoming transformer is very high due to low system resistance which is shown in simulation. Both current contain 68% second harmonic component. Protection using stabilized differential relay SPAD 346 C which is blocking based on the second harmonic of the differential current.

#### B. Circulating current minimization and protection

Circulating current depends upon secondary voltage difference and % impedance of paralleled transformer. In this case % impedance of transformer is very low. Due to this small voltage difference, high circulating current [9-10]

- Voltage difference at secondary terminal
  \[ ΔE_s = V_s * (E_s/E_{p1} - E_s/E_{p2}) \]

Where:
  - ΔEs = Voltage difference in secondary
  - Vs = Supply voltage
  - Es = Sec. rated voltage
  - Ep1 = Primary voltage across OLTC1
  - Ep2 = Primary voltage across OLTC2
  - P.U. difference in sec. voltage = ΔEs/Es
  - P.U. circulating current = P.U. ΔEs/(Zp.u.1+Zp.u2)
  - Actual circulating current = Ic(P.U.)*Ic(Base)

Mathematical calculation shown in Fig.4

### TABLE III

**COMPARISON OF CIRCULATING CURRENT WITH RESPECT TO % IMPEDANCE**

<table>
<thead>
<tr>
<th>T1 &amp; T2</th>
<th>HV1 HV2</th>
<th>HV1 HV2</th>
<th>HV1 HV2</th>
<th>HV1 HV2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HV1 Amp</td>
<td>HV1 Amp</td>
<td>HV1 Amp</td>
<td>HV1 Amp</td>
</tr>
<tr>
<td>8</td>
<td>79</td>
<td>230</td>
<td>305</td>
<td>559</td>
</tr>
<tr>
<td>10</td>
<td>63</td>
<td>191</td>
<td>316</td>
<td>447</td>
</tr>
<tr>
<td>12</td>
<td>53</td>
<td>159</td>
<td>263</td>
<td>372</td>
</tr>
<tr>
<td>14</td>
<td>45</td>
<td>136</td>
<td>226</td>
<td>319</td>
</tr>
<tr>
<td>16</td>
<td>39</td>
<td>119</td>
<td>197</td>
<td>279</td>
</tr>
</tbody>
</table>
To control secondary terminal voltage required voltage regulator relay SPAU 341 C1.

IV. SIMULATION RESULT

The short circuit analysis of the transformer is performed on the ETAP and PSCAD. Fault level calculation done using ETAP software for with and without parallel operation of transformer. Control switching scheme and inrush current done using PSCAD software.

1. ETAP simulation
   1.1. Fault level calculation of single transformer

   Fault level at 33 kV bus
   \[ = \sqrt{3} \times I_{sc} \times V_R \]
   \[ = \sqrt{3} \times 13.8 \times 33 \]
   \[ = 1297.47 \text{ MVA} \]

   Fault level at 33 kV bus for parallel transformer
   \[ = \sqrt{3} \times 22.7 \times 33 \]
   \[ = 1297.47 \text{ MVA} \]

2. PSCAD simulation
   2.1. Short circuit and inrush current for without parallel operation of transformer.

   Short circuit current depend upon system impedance and its peak depend upon x/r ratio. In Fig.8 shows connection diagram of existing short circuit laboratory which is perform short circuit test and short circuit current shown in Fig. 9 its maximum peak is 85.22 kA. Fig.10 and 11 shows inrush current in test object and testing transformer respectively.
2.2. Short circuit and inrush current for with parallel operation of transformer.

In Fig.12 shows connection diagram of proposed short circuit laboratory which is perform short circuit test and short circuit current shown in Fig. 13 its maximum peak is 93.44 kA. Whenever two and more than two transformers connected in parallel then effective impedance is reducing and short circuit current increase. If both transformers are energized at different moment then inrush current and sympathetic inrush current are realized in already connected transformer which is depended upon system resistance. Fig.15 (a) and (b) are showing both current due to parallel and parallel series transformer respectively. Proposed system can test higher rating of transformer, its means inrush current also increase which is shown in Fig. 14.

2.3. Inrush and sympathetic inrush current phenomena

Fig. 17 shows connection diagram for sympathetic inrush current no load configuration. These current depend upon many factor which is describe above but it’s mainly depends upon input fault level, If input fault level is high then sympathetic inrush is low and inrush current is high and vice-versa which is shown Fig.17 (a) and (b). Sympathetic inrush will persists for longer duration of time as compare to inrush current.
Capacity Enhancement Of Short Circuit Laboratory Using Parallel Operation Of Transformer

2.4. Circulating current simulation

Circulating current directly proportional to induced voltage difference at secondary terminal and limit by some of the % impedance of both the transformers. If % impedance of transformers is low then circulating current is high and vice-versa which is shown in Fig.21 and 22.

CONCLUSION

The paper presented solution to enhance capacity of short circuit lab by paralleling of short circuit testing transformer by simulating the same problem & phenomena viz. inrush and sympathetic inrush current which is mainly depend on system resistance. The circulating current is limited by the overall impedance of the circuit, which is usually the sum of the impedances of the transformers that are operating in parallel. The short circuit testing capacity of the transformer is reduced by the circulating current when the transformers are paralleled.

REFERENCES