The Field Test and Computer Simulation on the Inrush Current and Circulating Current of KEPCO's 765 kV Transformer

E. B. Shim*       J. W. Woo      G. J. Jung

KOREA ELECTRIC POWER RESEARCH INSTITUTE
(Korea)

SUMMARY
This paper describes the digital simulation and field test result of inrush current for the KEPCO's 765 kV transformer, which consists of 2 tanks in one phase, 666.7 MVA per phase. The peak inrush current histogram shows that the most of the cases are between 200 and 250 amperes, when the transformer was switched on from the primary side(765 kV), and the peak current was decayed as an half after the 7 second approximately. When the voltage was applied from the secondary side(345 kV), the peak current was between 250 and 350 amperes.

During the tap changing operation, the circulation peak current between left and right tank of transformer at tertiary winding was appeared up to 500 amperes, which forced to operate the current balancing relay. The field test result of circulation current at each tap shows up to 700 amperes in worst case which is little bit higher than that of simulation case. In the EMTP simulation, the circulating peak current was less than 50 amperes after dividing the current limiting reactor by two circuits. For the proper setting of relay protection schemes, the short circuit current between windings also measured and calculated.

Key words
Transformer, Inrush Current, EMTP, Circulating Current, Current Limiting Reactor

1. INTRODUCTION
KEPCO, the electric utility company of Korea, has been operating the 765 kV transmission line and substation since 2002. We confirmed the various electrical phenomena before applying the 765 kV voltage to the equipment which were developed by domestic manufacturer in order to confirm the reliability and soundness of it. Especially, we did not conduct the long term field test for the substation equipment such as 800 kV, 8 kA GIS(Gas Insulated Substation) and 2,000 MVA of transformer except factory test for it. So, we had applied the 765 kV voltage to the equipment from the secondary side for few months.

Based on the above background, we have compared the field test and simulated result of the inrush current of transformer when the voltage was applied from the primary side and secondary side. The 2,000 MVA transformer bank is consist of six single phase auto transformer with capacity of 333 MVA each, in order to transport by railway system. And it has current limiting reactor on the tertiary circuit to restrict the fault current. So, in addition to the inrush current, the circulation current between left and right tank of transformer at tertiary winding, when the tap changer is operating, was measured and calculated.

2. OUTLINE OF MODELING AND MEASUREMENTS
For the EMTP(Electro-Magnetic Transient Program) simulation, the saturation characteristics of iron...
n core, pre-insertion resistor, turn ratio of each winding, tap changer winding and current limiting react or are considered.

Fig. 1. Three Phase Diagram of 765/345/23kV Two Tank Type Transformer

Fig. 1 shows the three phase diagram of 765/345/23kV 2 tank type transformer circuit. In the field test of inrush current, the measurement was performed at each circuit of tertiary winding, and the each measured data was sum up by the software called TOP(The Output Processor). In order to compare the data with EMTP easily, the field test data was saved as IEEE COMTRADE type files.

2.1 SATURATION CHARACTERISTICS OF TRANSFORMER

From the test report of 666.6 MVA single phase autotransformer, we found that the exciting current is 0.5 percent of nominal current at the voltage of 1.0 p.u., 1.2 percent at the voltage of 1.1 p.u. and 2.0 percent at the voltage of 1.15 p.u. Using that above data, we converted it as current-flux curve as shown in table 1.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>10.67</td>
<td>1656.8</td>
</tr>
<tr>
<td>1.1</td>
<td>25.62</td>
<td>1822.5</td>
</tr>
<tr>
<td>1.15</td>
<td>46.69</td>
<td>1905.4</td>
</tr>
</tbody>
</table>

2.2 REPRESENTATION OF AUTO TRANSFORMER BY THREE WINDING TRANSFORMER MODEL IN EMTP

From In the EMTP, the auto transformer model is not directly available, so we should convert it to three winding transformer. In order to use the STC(Saturable Transformer Component) model in EMTP, the test result of short circuit impedance, winding resistance, load loss and no load loss are needed. The short circuit impedance between primary to secondary winding, between primary to tertiary winding
and between secondary to tertiary windings are 17.6%, 10.69% and 10.08% respectively. In tertiary winding, the short circuit impedance of current limiting reactor are included. This short circuit impedance of each winding can be expressed as following equations:

Thus, ohmic value of short circuit impedance of each windings are 51.5 ohms, -0.83 ohms and 2.68 ohms. From the open circuit test, the no load loss is 220 kilo watts. It can be expressed as an magnetizing resistance of 887 kilo ohms.

\[
Z_1 = \frac{1}{2}(Z_{12} + Z_{13} - Z_{23}) \quad [p.u.]
\]
\[
Z_2 = \frac{1}{2}(Z_{23} + Z_{12} - Z_{13}) \quad [p.u.]
\]
\[
Z_3 = \frac{1}{2}(Z_{13} + Z_{12} - Z_{23}) \quad [p.u.]
\]

Where

- \( Z_{12} \): short circuit impedance between primary and secondary winding (17.6%)
- \( Z_{13} \): short circuit impedance between primary and tertiary winding (10.69%)
- \( Z_{23} \): short circuit impedance between secondary and tertiary winding (10.08%)

### 2.3 OTHER EQUIPMENTS

The PIR (pre-insertion resistor) values is 520 ohms for 345 kV circuit breaker, and 800 ohms for 765 kV circuit breaker actually. But, in order to investigate the influence of resistor insertion, the PIR values are modeled from zero ohms to 1,000 ohms in steps of 100 ohms. In the field test case, we can not adjust the discrepancy of circuit breaker insertion time whereas insertion time is changed by "MONTE CARLO" method in EMTP simulation. So, the measured and simulated results can not be compared directly. Except for the PIR, we investigated the influence of capacitance of GIS.

### 3. ANALYSIS & FIELD TEST RESULT

#### 3.1 Inrush Current According to the PIR (Pre-Insertion Resister)

The inrush current of transformer is calculated as statistical analysis from 100 shots of closing case. As shown in table 2, the adoption of PIR clearly suppress the inrush current on both case, without the capacitance of GIS bus and with capacitance of GIS bus. The inrush current when the capacitance of GIS is neglected are little bit smaller than the cases when the capacitance of GIS is considered. This result explain that the charging current of GIS bus is included in the measurement of inrush current of transformer.

![Table 2. Inrush current prediction according to the PIR](image)

<table>
<thead>
<tr>
<th>PIR [Ω]</th>
<th>Primary side closing</th>
<th>Secondary side closing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>without capacitance</td>
<td>capacitance considered</td>
</tr>
<tr>
<td></td>
<td>without capacitance</td>
<td>capacitance considered</td>
</tr>
<tr>
<td>0</td>
<td>572.0</td>
<td>584.1</td>
</tr>
<tr>
<td>100</td>
<td>519.5</td>
<td>525.0</td>
</tr>
<tr>
<td>200</td>
<td>439.7</td>
<td>448.4</td>
</tr>
<tr>
<td>300</td>
<td>402.1</td>
<td>396.6</td>
</tr>
<tr>
<td>400</td>
<td>367.2</td>
<td>393.3</td>
</tr>
<tr>
<td>500</td>
<td>353.4</td>
<td>343.4</td>
</tr>
<tr>
<td>600</td>
<td>311.6</td>
<td>344.1</td>
</tr>
<tr>
<td>700</td>
<td>309.1</td>
<td>317.6</td>
</tr>
<tr>
<td>800</td>
<td>286.9</td>
<td>304.0</td>
</tr>
<tr>
<td>900</td>
<td>278.2</td>
<td>272.2</td>
</tr>
<tr>
<td>1,000</td>
<td>265.9</td>
<td>270.2</td>
</tr>
</tbody>
</table>

In the case the PIR is not used, the inrush current when the voltage is applied from the secondary side is 950 amperes approximately. Whereas, inrush current when the voltage is applied from the 765 kV side is 580 amperes approximately.

In the case the PIR is used, the inrush current is about 300 amperes on both cases however the secondary side closing case has little bit higher values.
3.2 Inrush Current Comparison (field test & computer simulation)

The figure 2 shows the example wave shape of EMTP simulation when the voltage is applied from the primary side, and the figure 3 show the field test wave shape for the same case.

The peak current of simulation & field test case for the inrush current is shown in table 3.

Table 3. Comparison of EMTP Simulation & Field Test Result when the voltage is applied from the 765 kV side

<table>
<thead>
<tr>
<th>Inrush Current</th>
<th>Field test case #1(Tr No4)</th>
<th>Field test case #2(Tr No5)</th>
<th>EMTP case</th>
</tr>
</thead>
</table>

Fig. 2. Inrush current, primary side closing(PIR= 800 ohms, EMTP)

Fig. 3. Inrush current, primary side closing(PIR= 800 ohms, field test)

In the case of secondary side closing case, the results are similar to that of primary side closing case. The figure 4 shows the example wave shape of EMTP simulation when the voltage is applied from the 345 kV side, and the figure 5 show the field test wave shape for the same case.

The peak current of simulation & field test case for the inrush current is shown in table 4.

Table 4. Comparison of EMTP Simulation & Field Test Result when the voltage is applied from the 345 kV side

<table>
<thead>
<tr>
<th>Inrush Current</th>
<th>Field test case #1(Tr No4)</th>
<th>Field test case #2(Tr No5)</th>
<th>EMTP case</th>
</tr>
</thead>
</table>
3.3 Circulation Current at the Tertiary Circuit of Transformer Bank

Fig. 4. Inrush current, 345 kV side closing (PIR= 500 ohms, EMTP)

Fig. 5. Inrush current, 345 kV side closing (PIR= 520 ohms, field test records)

Fig. 6. Single phase representation of the tertiary circuit of transformer bank with tap changer winding. (tap changer winding is common)
During the field test, we found that the circulating current between left and right tank of the tertiary circuit of the transformer bank is very high which forced to operate the current balancing relay. So we have measured the circulating current at the tertiary circuit of transformer for the each tap changer winding. The measured current was between 450 ampere peak and 700 ampere peak according to the tap changer winding ratio.

The six single phase autotransformer has six tap changer units, which has operation time difference during the tap changing operation, approximately 500 – 700 milli-second. It is very difficult to distinguish whether the circulating current happens due to tap changing operation or due to short circuit between the windings under this situation.

In order to investigate this phenomena, EMTP simulation was performed using the circuit shown in figure 6, which shows the single phase representation of the tertiary circuit of transformer bank. As shown in figure 6, the current limiting reactor is located between the tertiary winding(node name is "Y1_CA" to "AL1_B").

Figure 7 shows the measured wave shapes of circulating current during the tap changing operation, whereas the figure 8 shows the calculated for the same case. The peak current and wave shapes are identical between simulation and field test even though the initial part of the wave shape is little bit different. We guess that the main difference is due to the transfer resistance in real tap changer whereas the transfer resistance is neglected in EMTP simulation.

Because the impedance of tertiary winding is very low, the circulating current is circulating between left and right tank windings. If we can divide the current limiting reactor by two circuits, the circulating current will flows through the transformer tertiary winding and current limiting reactor winding.

We have calculated the circulating current when the current limiting reactor are divided by two as shown in figure 10.

![Fig. 7. Circulating current at the tertiary circuit of transformer bank (Field test record, tap changer is between 12 to 13)](image)

![Fig. 8. Circulating current at the tertiary circuit of transformer bank (EMTP case, tap changer is between 12 to 13)](image)

By dividing the current limiting reactor as two, the circulating current was down to 40 ampere peak.
which is less than 10 percent of previous case.

But, it is very difficult to divide the current limiting reactor actually, so we modified the protection scheme not to operate during the tap changing operation. The figure 9 shows the circulating current when the current limiting reactor is divided by two.

Fig. 9. Circulating current at the tertiary circuit of transformer bank (EMTP case, the current limiting reactor is divided by two)

Fig. 10. Single phase representation of the tertiary circuit of transformer bank with tap changer winding. (tap changer winding is common)

4. Conclusion

It was found from the simulation & field test result that the inrush current of transformer was identical, even though the discrepancy of the circuit breaker is out of control in field test case. From the test report at the factory test, we can successfully predict the inrush current by EMTP, and the field test result was in the estimated range.
The circulating current of tertiary circuit of transformer bank when the current limiting reactor is located between the left and right tank was very high, which forced to operate the protection scheme. We have found that the circulating current can be reduced to 40 amperes by dividing the current limiting reactor circuit as two circuit.

5. References