Abstract—Transformers are key components for electrical energy transfer in power systems. Stability and security of transformer protection are important to system operation; we found that many mal-trip cases of transformer protection are caused by inrush current problems. The phenomenon of transformer inrush current has been discussed in many papers since 1958 [1-5]. Therefore, this paper will only discuss and analyze inrush current problems. Finally, this paper will also present two cases that were analyzed with the use of digital simulation technique to make COMTRADE files, to provide over-current protection and differential protection tests and the analysis of the effect of inrush current on transformer protection.

Index Terms—Over-current protection, Differential Protection, Inrush Current, COMTRADE files.

I. INTRODUCTION

In power systems, differential protection is applied for transformer capacity above 10MVA, while over-current protection is used for transformer with the banks below 10MVA for main protection that includes simple theory and best protection results. However, the transformer will create large inrush currents when the transformer operates on no-load energizing condition. This inrush currents involves a large and long lasting dc component, which is rich in harmonics, assumes large peak values at the beginning about 6 to 30 times of the rated value. This condition causes unbalance of current loop of differential relay that will occur with mal-trip. In order to prevent false tripping due to an inrush current, a technique using the content of the second harmonic component in the current waveform is commonly used. However, this method cannot provide total solution for inrush current. Therefore, we present digital simulation method to analyze and to test to know the best transformer protection schemes.

II. SIMULATION AND ANALYSIS OF INRUSH CURRENT

The equivalent circuit of transformer model shown as Fig.1 consists of an ideal transformer of ratio $N_1 : N_2$ and parameter of elements. The model takes into account the winding resistances ($R_p, R_s$), the leakage inductances ($L_p, L_s$) and the excitation characteristics of iron core. The excitation characteristics of iron core can be expressed by equation (1) [8] which can show the excitation curve as Fig.2. Due to the non-linear of transformer iron core, this will result in excitation and saturation problems of transformer in power systems. According to different operation point of transformer core as Fig.3, we can get different excitation current on transformer. When switched to a no-load transformer, this will result in transformer’s working in saturation area of excitation curve (see Fig.3) in which creates high magnitude asymmetrical current with a high harmonic and a high direct current components. This may cause mal-operation of over-current protection or differential protection. Typically, for steady state operation, the excitation current of transformer is slightly less than 5% of the rated current (see Fig.3). In practice, the magnitude and duration of transient inrush current depend on the following [9]:

- Circuit breaker switching angle when the transformer is energized
- The value and sign of the residual flux linkage in the transformer core
- The saturation characteristic of the transformer core
- Source impedance

$$\varphi = -s^* [I_{sat} \cdot \tan^{-1}(-s^* \cdot (d\varphi/dl) \cdot I_e - I_s) - s^* \cdot \varphi_e \cdot I_e + \varphi_{sat}] \tag{1}$$

Where: $s = 1$ for an ascending trajectory, $s = -1$ for a descending trajectory
- $I_{sat}$ for saturation current of transformer
- $d\varphi/dl$ for slop of excitation curve of transformer
- $I_e$ for excitation current
- $I_s$ for coercive current
- $\varphi_e$ for residual flux
- $\varphi_{sat}$ for saturation flux of transformer
Fig. 2 Excitation curve of transformer

Fig. 3 The operation point of excitation curve determines the magnitude of the excitation and inrush current

Fig. 4 shows the simplified single-line diagram of transformer protection scheme used in TPC’s (Taiwan Power Company) substations. We will simulate a transformer running in no-load situation. Table 1 shows the parameters of the simulation system. Typically, the simulation results of the inrush current are shown in Fig. 5. At the same time, the field test result is presented in Fig. 6. Those currents of all figures are used to CT (Current Transformer) secondary values whose ratio is 1200:5. The inrush current is about 5 times larger than the rated current of the transformer. The large inrush current will hit transformer protection, which causes mal-trip for different protection or over-current protection. We will discuss these issues in the next section. Here, inrush currents are formed based on the following three major factors: the transformer energized angle, residual flux of iron core and structure. Fig. 7 shows the relations between peak values of three-phase inrush currents and CB1 closed angles when the residual flux of transformer is zero. Fig. 8 and Fig. 9 show Peak values of inrush current vs. residual flux (from -1 to 1 pu) when CB1’s closed angle is 0 degree and 90 degrees respectively. The simulation results show that the inrush current can be reduced by controlling CB1’s closing time and residual flux. For example, according to Fig. 1, we can write equations as follows:

\[ V_p = R_p I_p + L_p \frac{dI_p}{dt} + N_1 \frac{d\phi_m}{dt} \]  \hspace{1cm} (2)

\[ V_s = R_s I_s + L_s \frac{dI_s}{dt} + N_2 \frac{d\phi_m}{dt} \]  \hspace{1cm} (3)

When the transformer is energized in no-load, the equation (3) can be expressed by:

\[ \phi_m = \frac{1}{N_2} \int V_s dt \]  \hspace{1cm} (4)

Here, we want to get CB1 optimal closed time in the main flux (\( \phi_m \)) close to zero. Because the number of turns of primary \( N_1 \) is larger than the item of \( \int R_p I_p dt \) and \( L_p I_p \), we can modify the equation (4) as follows:

\[ \phi_m = \frac{1}{N_1} \left[ \int (V_p - R_p I_p) dt - L_p I_p \right] \approx \frac{1}{N_1} \int V_p dt \]  \hspace{1cm} (5)

Therefore, the value of main flux (\( \phi_m \)) can be calculated at any instant using equation (5). In order to reduce inrush currents, we can use the main flux information combined with zero-crossing detector to determine the CB1 closing time, which is at main flux (\( \phi_m \)) zero. The simulation result is shown in Fig. 10. All of the inrush currents are reduced by controlling CB1’s closing time.

<table>
<thead>
<tr>
<th>Voltage Rating</th>
<th>161 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>System frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Equivalent Source Impedance:</td>
<td></td>
</tr>
<tr>
<td>( Z_{at} = 0.238 + j5.72(\Omega) )</td>
<td>( Z_{st} = 2.738 + j10(\Omega) )</td>
</tr>
<tr>
<td>Transformer Specification:</td>
<td></td>
</tr>
<tr>
<td>3 Phase ; 161kV/69kV/11kV</td>
<td>200MVA/200MVA/66MVA Y/Y/D1</td>
</tr>
<tr>
<td>[ Z_y = 0.2203 + j17.2505 (\Omega) ]</td>
<td></td>
</tr>
<tr>
<td>Based on 161kV</td>
<td>[ Z_s = 0.1296 + j1.287 (\Omega) ]</td>
</tr>
<tr>
<td>[ Z_t = 0.7123 + j26.7275 (\Omega) ]</td>
<td></td>
</tr>
<tr>
<td>Based on 11kV</td>
<td>[ Z_x = 303.91 - j3944.76 \mu(\Omega) ]</td>
</tr>
</tbody>
</table>

Table 1 The parameters of the simulation system
Fig. 4 Simplified single-line diagram of transformer protection

Fig. 5 Inrush current simulation result

Fig. 6 Inrush current field test result

Fig. 7 Peak values of inrush current vs. CB1 closed angles

Fig. 8 Peak values of inrush current vs. residual flux (from -1 to 1 pu) when CB1’s closed angle is zero degree
**Fig. 9** Peak values of inrush current vs. residual flux (from -1 to 1 pu) when CB1’s closed angle is 90 degrees.

**Fig. 10** Inrush currents compare CB1 uncontrolled with CB1 controlled.

### III. Practical Examples and Results of the Effect of Inrush Current

In this section, we will use two cases to explain and analyze how and why the protective relay mal-trip occurs in inrush currents. Case I for the mal-trip of differential protection relay occurs during the time when transformer is energized in no-load. Case II for the mal-trip of over-current relay of transformer neutral line is caused by transformer when it is energized in no-load.

**Case I:** The connection diagram of differential relay of transformer is as shown in Fig. 4. The basic theory of differential relay is formed with the use of current balancing of transformer of the two-sides as a trip signal. When the unbalance currents of transformer of the two-sides is larger than the pick-up setting of differential relay, the trip signal will be sent from differential relay to trip circuit breaker (CB) for isolated fault. From the basic differential theory, we know that the inrush currents only go through one of the transformer winding when the transformer is energized in no-load. At this time, if the differential relay of transformer doesn’t include the best blocking function of the inrush currents, than the mal-trip will occur. The differential relay of transformer use either harmonic or blocking principles for inrush currents of transformer. Generally speaking, the second-harmonics content of inrush currents of transformer usually is 15% larger than the fundamental component. Therefore, the setting of the second-harmonics of differential relay is usually set at 15%

In the Fig.4, the frequent mal-trip of differential relay is caused by the inrush currents when the transformer is energized in no-load. Here, the differential relay is electrical-mechanical type that utilizes the second-harmonic blocking for inrush current restrain. The setting of the second-harmonic is at 15%. Fig. 11 shows the situation when the traces of inrush current is entering the protection zone of differential relay during the transformer is energized in no-load. Fig. 12 is the second-harmonic contents of the inrush currents after it is transferred by Fourier transfer. We can see the second-harmonic contents of the inrush currents of phase A, B and C at 10–12%, 20–23%, and 19–35% respectively. It is very obvious that the second-harmonic contents of phase A is less than 15%, so the mal-trip of differential relay of phase A usually occurs in transformer when it is energized. In order to improve this situation, we adjusted the setting of the second-harmonic from 15% to 10% and since then the differential relay has never mal-tripped during the time when the transformer is energized in no-load.

**Fig. 11** the traces of inrush currents
Fig. 12 Second harmonic contents of inrush currents

Fig. 13 shows one-line diagram of generator’s cooling pump systems at a power plant in Taiwan. Here, the cooling system is very important for generators. If the cooling system shut down, then all the generators will be tripped by over-heating. The loss power of the load of transformer (TR-SW2) results from the mal-operation of TR2_CB1 by operators and the factor that the TR2_CB2 remains closed. At the same time, the transformer (TR-SW2) only produces inrush current when the Tie CB is closed. The inrush currents results in the mal-trip of over-current relays (50/51Z, the relay setting is 4A for instant trip) of two transformers’ (TR-SW1 and TR-SW2) neutral-line. The current waveforms are shown in Fig. 14 and Fig. 15. In order to solve the mal-trip of 50/51Z, we designed an inter-lock logic of the Tie CB as Fig. 16 for security and reliability of a power plant. This logic can keep Tie CB working in normal condition. In general condition, when we close the Tie CB, the currents waveforms of the transformers’ (TR-SW1 and TR-SW2) neutral line are shown in Fig. 17 and Fig. 18. The results are satisfying because the magnitude currents are less than the setting (4A) of the relay. Therefore, the systems can work in the best condition.

Fig. 14 Current of neutral line of TR-SW1 when TR2_CB1 is opened

Fig. 15 Current of neutral line of TR-SW2 when TR2_CB1 is opened

Fig. 16 Improvement logic of case study of inrush currents
IV. TRANSIENT TEST ON DIFFERENTIAL PROTECTION

Nowadays, the fault and transient data recording are widely used in power systems. Their data are being used with various devices to enhance and automate the analysis, testing, evaluation, and simulation of power systems and related protection schemes during fault and disturbance conditions. In order to get a bridge between different electric devices, IEEE defines a common language that is a common format for transient data exchange (COMTRADE, IEEE C37.111) for a standard format for the exchange of data in 1991. Here, we will use digital simulation to produce COMTRADE file for transient tests of differential protection.

Fig. 19 shows a transient test structure of differential relay for transformer protection. We use simulation tools of PSCAD and MATLAB to simulate a number of different fault types and to produces COMTRADE files for transient test of differential relay. The transient tests of open loop are used to input COMTRADE file to wave amplifier that produce real currents or voltages to inject into protection devices for performance evaluations of protective relay. In addition, this method can be combined by GPS (Global Position System) for end-to-end test. Fig. 20 shows the inrush current for differential relay test. A transient test of transformer internal-fault (AG) is shown in Fig. 21. The differential relay is operated because the differential current trace of phase A falls into the operation area of differential curve. On the contrary, in Fig. 22, the differential relay is of no-trip when the external fault occurred in out of the protection zone of differential relay of transformer. The transient test can nearly simulate real situation of differential protection of transformer to clearly show whether the differential relay should be operated or not in the internal or the external faults. However, the traditional steady-state test cannot control dynamic processes, namely, internal faults, external faults, energized and saturation of transformers. Usually, it is discussed when the faults are occurred. From the above discussion, the transient test of protective relay is important for power systems protection.
CONCLUSIONS

This paper provides detail analysis of simulation and field measurement for problems of inrush current and transformer protection. At the same time, we have also identified mal-trip factors from our case studies in differential relay and over-current relay, as well as resolutions for improvement. In addition, in protection test field, we present advanced transient test method that is applied in the setting of relay, fault analysis and new algorithms research of relay and so on, which will result in better performance in transformer protection and thus
saibility, reliability and security of power systems operation can be reached.

REFERENCES


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