Ferro-Resonance Analysis and a 10 kV Ferro-Resonance-Free Magnetic Potential Transformer (MPT) Design

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INTRODUCTION

The importance of the electrical grounding is well-known. According to the definition given by NEC, it can be divided into many types: system grounding, equipment grounding, surge-arrester grounding, safety grounding (personnel), electronic-equipment grounding, and mine-system grounding. The historical review given here is limited to system neutral-grounding. The electricity was first available in China around 1879. take Shanghai for example, 2kV cable supply was installed in 1904, 6.6kV in 1911, 23kV in 1916 and 33kV in 1932. Before 1952, the national agreement about system grounding was not available, and the systems were usually ungrounded. After 1954, with the development of the electrical power industry, and following the recommendation of former Russian, 6-23kV systems kept ungrounded or tuned-reactor grounded, and 35-66kV systems were changed to tuned-reactor grounding including cable systems. Years later, with the power system increasing in size, many serious power system failures had taken place because of improper grounding methods or due to the unfavourable cost of ground-resistance systems. One of those serious problems is the ferro-resonance over voltage/extreme current in ungrounded power system, and another is the unfavourable performance of tuned-reactor for cable distribution system. Individual actions had been taken to solve the problems caused by above issues, however, it is indispensable to make a national agreement. In 1994, a national agreement named “Over voltage protection design criteria for 3-220kV AC electric power projects” come into effect. Then, the system grounding methods become flexible and optional following the criteria of safety and economic and according to the system condition.

Although the effective design criteria for system grounding is available, the existing improperly grounded systems are still in operation. So that, the ferro-resonance over voltage or/and extreme current is still a critical problem in China. Ferro-resonances in the transmission network can always be traced to a series resonance circuit with at least one non-linear energy device like MPT, power transformer and one linear energy device of corresponding capacitance. In the 6-35kV ungrounded systems in China, the ferro-resonances are always resulted from a series resonance with a saturated MPT and the system capacitance. The features of the ferro-resonance in power system are [1]:

- The non-linear device is the harmonic-source, it may cause to resonate only when the system capacitance is matched and meet the equation of:

$$2\alpha_{mL} = (2\alpha_{mC})^{-1} \quad (1)$$

Here: $n$ is the order of harmonic,
$L$ and $C$ are respectively the non-linear inductor and the system capacitance.

According to above analysis, we can eliminate ferro-resonance mainly along three different ways as below:

- Enlarge the ferro-core area of a MPT and improve its magnetization characteristics.
- Calculate the system parameters $L$ and $C$ in advance to avoid resonance conditions.
- By using damping resistance (or reactor).

Unlike the existing methods for ferro-resonance mitigation, this paper is aimed to investigate a ferro-resonance-free MPT to avoid it occurrence in advance rather than to damp it afterwards. After testing and analysing two magnetic samples (ordinary ferro-core and technically treated ferro-core), the results concluded are: 1> the larger the area of the MPT ferro-core, the less probability for high-harmonic resonance to occur, 2> the steeper the linear region of the MPT $B - H$ curve (soft magnetic material), the less probability for sub-harmonic resonance to occur. Based on above conclusions, a 10 kV ferro-resonance-free MPT was developed, whose ferro-core is technically treated and 1.8 times of the ordinary MPT. A prototype, which is different from that published on CIGRE [2] in principle, was also made by Han-Kou MPT Factory (HKF) in Wuhan, China. The simulation experiment is designed based on the principle of Solt-Peterson Loop, and the results from simulation are included in the paper to support the conclusions.

A HISTORICAL REVIEW OF NEUTRAL SYSTEM GROUNDING IN CHINA

In [3], the author provides a historical development of neutral-grounding practices looking back on 40 years. The authors summarised the neutral grounding methods of solidly grounded, low-resistance grounding, high-resistance grounding and ungrounded systems in turn [4]. To avoid unnecessary repetition, the special attention in this paper is focused on tuned-reactor grounding method, and the application of low-resistance grounding method for medium cable systems.
Refer to Fig. 1 for the panorama of the power system grounding historical development in China. Where:

\[ X_1, \ X_0 \text{ and } R_0 \] are respectively positive-sequence reactance, zero-sequence reactance and zero-sequence resistance.

\[ 3I_{c0} \] is the single phase ground fault (capacitive) current of the un-grounding system.

LV: Low voltage systems (110-400V)

MV: Medium voltage systems (3-66kV)

HV: High voltage systems (110-220kV).

Before 1952

- Ungrounded

From 1954 to 1987

- Solidly grounded (LV, HV)
- Ungrounded, OR , tuned reactor

After 1987

- HV: Solidly grounded, Low-resistance grounded, Ungrounded IF: \(0 < X_0/X_1 \leq 3\),
- MV: Tuned reactor, OR Ungrounded
- IF: \(3A(3-6kV), 20A(10kV), 3A(10 5kV)\)
- IF: \(3-20kV\)
- Generators: Tuned reactor, OR Ungrounded
- IF: \(3A(6.3kV), 3A(10 5kV)\)
- IF: \(3-35kV\)
- Cable systems: Low-resistance grounding is

Fig. 1. The panorama of The system grounding practices in China.

1. **Solidly grounded**

Nowadays, almost all the HV and LV systems in China take this grounding method. In order to improve the reliability of HV systems, the HV breakers always re-close once with a short delay for insulation recovering after fault shutdown.

2. **High-resistance grounding**

This is the grounding method of choice for drive system. However it can be applied to MV systems [4], and it also shows advantages in LV systems [5]. In China, this method is seldom applied for practical engineering, but, it is an acceptable choice in 6-10kV over-head transmission systems.

The authors of this article are confident that this grounding method is applicable to both LV and MV systems in China in the near future. In USA, the discriminator of taking high-resistance grounding is \(R_0 \leq X_{c0}\) (here, \(X_{c0}\) is the single phase capacitance impedance).

3. **Low-resistance grounding**

By taking this grounding method, the ground fault current is in the range from 25 Amperes to several hundred Amperes. Meanwhile, in order to mitigate the instant over voltage, the impedances need to meet the relationship of: \(R_0/X_0 \geq 2\).

Like the solid grounded systems, the low-resistance grounded systems provide effective control to safe levels of the over voltage generated in the power system by resonance and re-striking ground faults. Anywhere, low voltage drive systems are rarely grounded through a low resistance as an immediate shutdown of the processes occurs in this grounding system. In China, it is widely used in the MV cable systems. Shanghai has a long operation history of the low-resistance grounded cable systems. In 1919, four 23kV cable lines were in operation (8.64km long for each), and the neutral systems first grounded by the 8Ω resistor (two installed, one in operation and one spare). Then, it extended to the other cables systems in Shanghai, 5.7Ω for 10kV systems, 4Ω (or partially 3.81Ω) for 6.0/6.6 kV systems, and, in 1987, the 35kV cable systems were changed from the tuned reactor grounded to 9.9Ω resistance grounded. Currently, this method is widely used in many other cities for MV cable systems in China like Guangzhou and Wuhan. Surely, the operation experience shows that it is an effective method for MV cable systems. However, as some people have concerns, we must carefully design this type of system to ensure its reliability, safety, and the influence they have on communication systems.

4. **Ungrounded**

In the past, the ungrounded system was extensively used with the assumption that it is more reliable. Unfortunately, experiences with multiple failures due to arcing ground faults, ferro-resonance, insulation brake-down and other types of failures, make us to limit the use of ungrounded systems.

5. **Tuned-reactor grounding**

Once as the only answer for MV system grounding in China and former Russian, this method is effective for MV over-head transmission systems. Anyway, with regard to its application for large cable system, it suffers the following disadvantages:

- It can not take its responsibility of “arc-suppressing” to extinguish the arc of the arcing ground fault, as the faults occurred in cable systems are usually “permanent”.
- Single-phase-to-ground faults sometimes develop serious failures while taking manual ground-fault-localization. Although the high technical fault-location devices are available nowadays, they are costly.
• It is difficult to select the capacity of the tuned reactor as the system parameters are always changeable, and sometimes the tuned reactor becomes disconnected with the system (location problem).

For above reasons, we must carefully select the location of the ground point and the capacity of the tuned reactor. In China, we must take 5-10 years future-plan for consideration to calculate the capacity $W$ (kVA) [6]:

$$W = 1.35(3I_{c0})V_n / \sqrt{3}$$  \hspace{1cm} (2)

Where:

$V_n$ (kV) is the connected system rated voltage.

FERRO-RESONANCE ANALYSIS [7]

For a thorough understanding of the Solt-Peterson Loop (SPL), we use the circuit in Fig. 2 to test a 10kV ordinary MPT and compared with that of SPL. The results tell us that:

• The better the V-A curve of the subject, the less resonance occurrence “area”.

• There is no resonance to occur if:

$X_{c0} / X_{le} \leq 0.01, (or, \geq 3)$ (SPL result)  \hspace{1cm} (3)

$X_{c0} / X_{le} \leq 0.015, (or, \geq 1.7)$ (our test result)  \hspace{1cm} (4)

Here: $X_{le}$ is the single phase impedance of the MPT under rated system voltage.

Inspired by above conclusions, we can “improve” the MPT parameters to avoid ferro-resonance. So that the next job is to find out how to improve it.

Additional to all the instruments shown on the circuit, we use a mA-current meter and a 0~150~300 volt-meter to take the actual readings.

The results recorded are described by MATLAB as Fig. 4.

![Fig. 3, The sample-core shape and dimension](image)

![Fig. 4, The B-H curves of the two samples](image)

**FERRO-RESONANCE FREE MPT DESIGN**

In order to analyse the results of the tested samples, we use functions-of-fit to formulate the Volt-Ampere (B-H) relationship as in the form of:

S2: $\phi_1 / \phi_2 = 45 / 67.5, h = 30, w_1 / w_2 = 150 / 200$

S1: $\phi_1 / \phi_2 = 46 / 65, h = 30, w_1 / w_2 = 150 / 200$

Where:

$w_1$ & $w_2$ are respectively the number of primary and secondary wirings.
\[ i = f(v), OR, i = f(\psi). \]

Here, \( i, v, \psi \) are respectively the current, voltage and the magnetic flux of the samples.

The theoretically analysed results are shown on Table-1.

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