

VERIFICATION OF UTILITY REQUIREMENTS ON MODERN NUMERICAL TRANSFORMER PROTECTION BY DYNAMIC SIMULATION

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INTRODUCTION

Power utilities are aware of the specific characteristics and requirements for their network. For this reason, they may require additional functionality from the protective devices and secondary systems included in their power network. Therefore ECEPA requires a number of specific tests to be conducted on the protection system proposed for a particular application to prove the suitability of the proposed protection system for the specific application, as in Xiang (1). Only when all of these tests are successfully passed, the protection system is certified for use in ECEPA's network.

The 500/230kV autotransformers are extremely important power transmission elements in ECEPA's network. Most of these autotransformers consist of three single-phase transformer units. Protection systems for these autotransformers have to fulfil very strict requirements, which are set down by the utility.

TEST SYSTEM SET - UP

ECEPA's analogue power system simulator was used to perform all tests. The simulator can incorporate the analogue models of lines, transformers, generators etc. For the autotransformer protection testing, the simulated test system was therefore set-up in accordance with single-phase transformer units. The tested power system with the tested internal and external fault positions is shown in Figure 1.

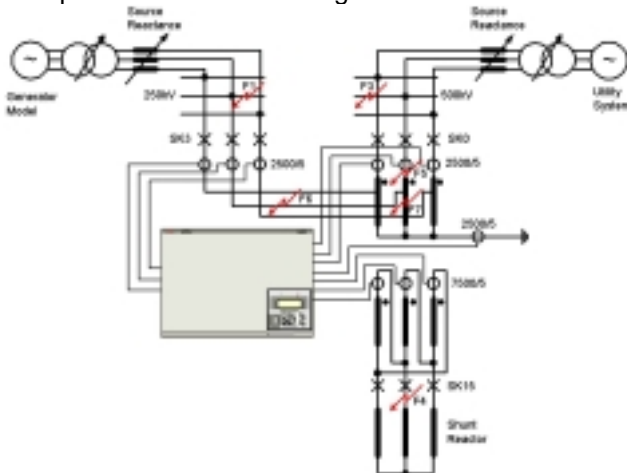


Figure 1: Test system set-up

Autotransformer Model Description

The common and serial windings of the autotransformer model consist of more than twenty coils with independently connectable taps in order to facilitate autotransformer connection with different turns ratio, faults close to the neutral, turn-to-turn faults involving any number of shorted turns etc. The LV winding has the similar construction. By changing the relative position of the coils and the size of the air-gap of the iron core, the leakage impedance and magnetising impedance of the autotransformer model can be adjusted. The three single-phase transformers were connected in such a way to form three-phase autotransformer with Yy0d11 vector group connection. The equivalent data for three-phase autotransformer model are given in Table 1.

TABLE 1: Equivalent Autotransformer Data

| | Rated Power [MVA] | Rated Voltage [kV] | Rated Current [A] |
|------------|-------------------|--------------------|-------------------|
| HV Winding | 1082 | 500 | 1250 |
| MV Winding | 1082 | 250 | 2500 |
| LV Winding | 541 | 115 | 2716 |

Protection System Connections and Settings

Overall three winding biased differential protection function (ANSI device No 87T) with additional unrestrained operating level (ANSI device No 87H) and low impedance restricted earth-fault protection function (ANSI device No 87N) were activated within protection system during all tests. All ten currents connected to the protection system were recorded during all tests, as shown in Figure 1.

The differential function (87T & 87H) has measured the three-phase currents from all three sides of the protected autotransformer. However it shall be noted that currents from the LV side were located inside of the delta winding. Therefore measured currents on all sides were in phase. Due to that fact, autotransformer vector group was set as Yy0y0 in the protection system. Automatic deductions of the zero-sequence currents for the differential function were enabled on all three sides within the protection system. This was done in

order to prevent the unwanted operation of the transformer differential function during external single-phase to ground faults on 500kV or 250kV side. The cross blocking between the phases was always disabled. Therefore during any inrush conditions each phase individually had to restrain and prevent unwanted operation only on the measurement available from that phase. The minimum pick-up current for the transformer differential function was set to 30% on the protected autotransformer base of 1082MVA. The differential function overall operating characteristic is given in Figure 2.

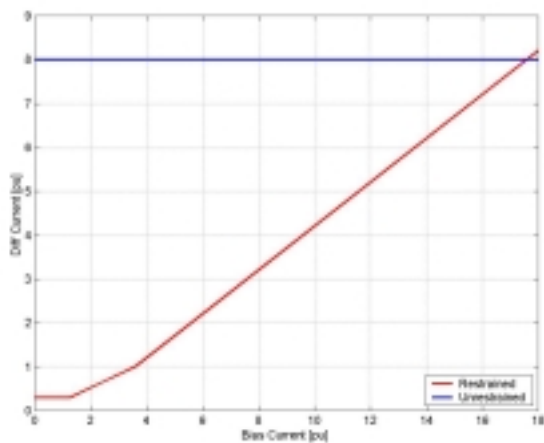


Figure 2: 87T & 87H operating characteristics

The restricted earth-fault function (87N) measured two sets of three-phase currents from 500kV and 250kV sides and one single-phase current from the autotransformer common neutral point. The minimum pick-up current for the restricted earth-fault function was set to 30% on the base of rated current for the 250kV winding. Its overall operating characteristic is given in Figure 3.

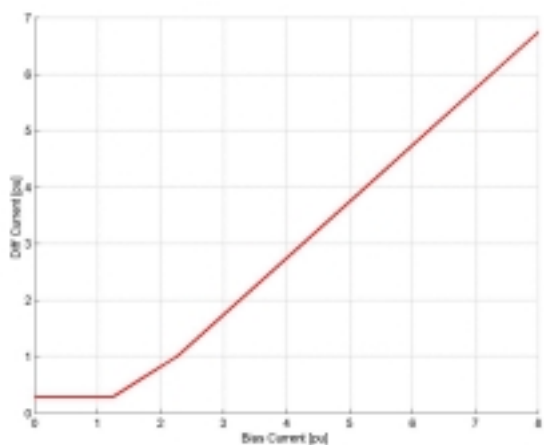


Figure 3: 87N operating characteristic

DYNAMIC TESTS

More than two hundred dynamic tests were performed during the testing. Different types of internal fault, external fault, involving faults, inrushes etc. were simulated. However, the paper will concentrate primarily on internal transformer fault types that are very specific for the transformer protection and usually provide difficult operating conditions for the transformer protection system.

Internal faults followed by CT saturation

Traditionally the second harmonic blocking is used in order to restrain the transformer differential relays during inrush condition. However it is known that the second harmonic blocking can prevent or delay the operation of the differential relay for internal faults followed by CT saturation, as in Kasztenny et al (2), Sidhu et al (3) and Mikrut et al (4). The behaviour of the protection system during such operating conditions was tested. First the protection system was set-up in the traditional way. The second harmonic blocking was always active, and the set level for this restrain criterion was 15%.

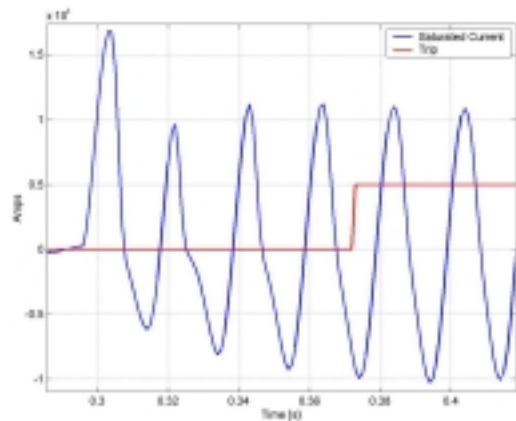


Figure 4: Late 87T trip due to traditional use of 2nd harmonic blocking criteria

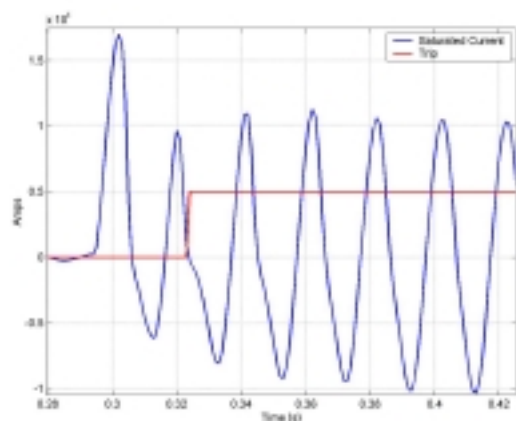


Figure 5: Fast 87T trip due to adaptive use of 2nd harmonic blocking criteria

After this test, the unique feature of the protection system, to adaptively use the second harmonic blocking was enabled. No any other setting parameter was changed. Then the operation of the differential function for internal faults was not effected at all by presence of second harmonic due to distorted CT secondary current, as shown in Figure 5.

These tests show that modern numerical protection system can adaptively use the second harmonic blocking criteria. The protection system can utilise it as restrain quantity during inrush conditions, but disregard its delaying influence during internal faults. This feature insures much quicker operation of the differential function within numerical protection system for internal faults followed by CT saturation.

Internal turn-to-turn faults

The turn-to-turn fault is a unique type of fault appearing only in electrical machines (i.e. transformers, generators and motors). The main problem with this type of fault is that the terminal currents are almost not effected at all, but the currents in the shorted turns can be many times higher than the rated winding current.

The differential protection function is the only electrical protection, which can detect this type of fault. Turn-to-turn faults were simulated in serial, common and LV autotransformer windings. The influence of the different fault locations within the winding was checked. The following table summarises the test results for several test cases.

TABLE 2: Summary for Turn-to-turn Faults

| Fault Position | Percentage of shorted turns | Differential current |
|----------------|-----------------------------|----------------------|
| Common Winding | 1% | 0.12 pu |
| Common Winding | 2% | 0.62 pu |
| Serial Winding | 1% | 0.11 pu |
| Serial Winding | 2% | 0.55 pu |
| LV Winding | 6% | 1.42 pu |

During these tests, the differential function detected and tripped all turn-to-turn faults, which had two or more percents of shorted turns.

Internal winding-to-earth faults

The internal winding-to-earth fault is unique type of fault appearing only in electrical machines. The fault voltage varies in proportion to the fault location within the winding. It has the full phase-to-

earth voltage value for faults close to the winding bushing and value almost down to zero volts for fault close to the autotransformer neutral point. The most difficult faults to detect are the faults close to the neutral point. For these faults the terminal currents are almost not effected at all, but the current in the autotransformer neutral has very high value irrespective of the fault location in the winding. This is practically the major difference in comparison with the turn-to-turn faults.

The restricted-earth-fault protection function and the differential protection function are the main electrical type protections for this type of fault. However due to the fact that the neutral current is always high for this type of faults, restricted-earth-fault protection function has shown distinct advantages for fast disconnection of autotransformer for this type of internal fault. Winding-to-earth faults were simulated in serial and common autotransformer windings. The following table summarises the test results for several test cases.

TABLE 3: Summary for Winding-to-earth Faults

| Fault Position | Percent of involved turns | Fault Resistance | Neutral Current |
|----------------|---------------------------|------------------|-----------------|
| Common Winding | 1% from neutral | 0 Ohms | 8.4 kA |
| Common Winding | 2% from neutral | 0 Ohms | 10.0 kA |
| Common Winding | 2% from neutral | 6.5 Ohms | 0.75 kA |
| Common Winding | 4.3% from neutral | 6.5 Ohms | 1.6 kA |
| 250kV Bushing | 50% from neutral | 0 Ohms | 13.2 kA |
| 500kV Bushing | 100% from neutral | 0 Ohms | 9.9 kA |
| 500kV Bushing | 100% from neutral | 60 Ohms | 3.0 kA |
| 500kV Bushing | 100% from neutral | 100 Ohms | 1.9 kA |

The restricted earth fault function successfully detected and tripped all winding-to-earth faults regardless of the percentage of involved turns and fault resistance.

Energising of faulty autotransformer

After a couple of incidences in China with energising of faulty transformer, followed by failure of the protection system to operate for these conditions, the local utilities have set-up very strict requirements on new transformer protection system for these type of operating conditions. Therefore, all types of internal faults including turn-

to-turn and winding to earth faults must be tested during dynamic simulations. The numerical protection system successfully detected and cleared all of these types of faults.

For simplicity, the results of only two test cases are presented in this paper. Both test cases represent switch-on of the autotransformer from the 500kV side. However, in both cases the transformer had internal earth fault, which was quickly detected and tripped by the numerical protection system. For these two test cases direct pictures from the disturbance evaluation tool are shown in Figure 6 and Figure 7.

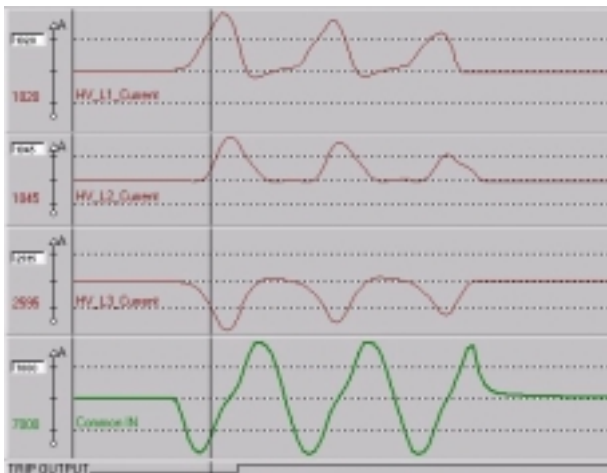


Figure 6: Energising of faulty autotransformer with internal Phase L3-to-earth fault

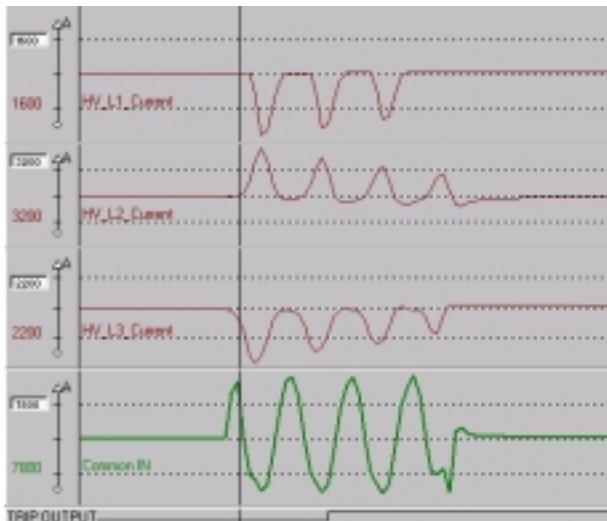


Figure 7: Energising of faulty autotransformer with internal 2% winding-to-earth fault

CONCLUSION

The dynamic tests have verified that the modern numerical transformer protection system can fulfil very demanding requirements set by the power

utility. The key to the success was the capability of the protection system to combine the overall transformer differential function (ANSI No 87T & 87H) with the numerical restricted-earth-fault protection function (ANSI No 87N). During all dynamic tests, these two protection functions worked in perfect harmony complimenting each other for different difficult test cases, as in Bin (5).

The numerical transformer protection system showed the following capability:

- to detect and trip all turn to turn faults with two or more percent of shorted turns
- to detect and trip all winding-to-earth faults, even the one located only one percent away from the common neutral point
- to detect and trip all evolving faults
- to detect and trip all types of internal faults during switch-on of the autotransformer
- to remain stable for all magnetic inrushes
- to remain stable for all external faults

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