Simulation of Resonance Over-voltage during Energization of High Voltage Power Network

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***Abstract* – Under network equipment outage conditions, the system has to be restored to normal operating conditions as fast as possible to ensure the supply security and avoid prolonged interruption of power supply. In the development of the restoration strategy under different contingencies, a wide range of issues is needed to be studied. For different contingencies, it is important that appropriate approaches, tools and study models are selected and used to meet different objectives.**

The extraordinary system conditions during restoration require special electromagnetic transient analysis with different system modelling methods and system parameters. All these are very different from those studies conducted for normal operating conditions. Field tests of various restoration arrangements also play an important role in calibrating the study models and parameters in order to verify the study results. With all these studies, CLP Power is able to establish practical and reliable system restoration plans.

Keywords – Temporary over-voltage, resonance, power system restoration, insulation coordination, power system simulation and field tests.

I. INTRODUCTION

CLP Power operates a vertically integrated electricity generation, transmission and distribution business to serve about 80% of the population in Hong Kong Special Administrative Region. The maximum local demand in 2001 was 5844MW. The transmission and distribution network comprises more than 10,800 km of overhead line and cable with voltages ranging from 11kV to 400kV.

It is the key objective of CLP Power to provide a stable and reliable power supply to its customers. Under different situations, such as supply restoration after large disturbance, energization of various system equipment is required to restore the system to normal operating conditions as fast as possible in a safe and efficient manner.

However, as the network configurations under outage conditions are much different from the normal system running arrangements, the restoration plan of the network requires a detailed study in the planning stage to assess the feasibility and risk involved as well as to develop an optimal system restoration strategy.

The most direct way to assess the feasibility and risk of the restoration plan is by conducting field tests. However, apart from the high degree of risk anticipated, field tests require resources and network outages which may affect the supply reliability. It is also not practical to test all configurations and operating conditions in the restoration plan. Furthermore, in many cases field tests could not be conducted due to operational limitations.

Simulation study has the flexibility to model and analyse different network configurations and system conditions for the restoration plan. However, the accuracy of the models and hence the results are sometimes questionable. To solve this problem, CLP Power has adopted a hybrid approach to assess the feasibility and risk of the restoration plan by combining simulation study with field tests.

This paper describes the resonance over-voltages encountered during the energization of transformers in transmission systems and the use of simulation method for resonance analysis and formation of risk mitigation measures.

II. STUDY FOR POWER SYSTEM RESTORATION

The major objective of power system restoration study is to develop an optimal restoration strategy to ensure an efficient and reliable process of restoration of supply to the customers with the shortest time while maintaining the stability and security of the system and the safety of its related equipment during the restoration process.

The system characteristics and behaviour during the restoration process are highly non-linear and complex. The extraordinary system configurations and the operating conditions may result in system response beyond the scope of normal operations. Because there are many complex and different problems to be solved in the restoration study, it is more effective to break down the big problem into small ones and analyse them one by one with appropriate analysis tools.

A wide range of issues is needed to be studied at the planning stage to identify the risk associated with the system characteristics and performance under restoration conditions and to develop mitigation measures if required. Besides the capability of the generating plants and their auxiliary equipment for restoration, the most commonly performed studies are analyses focused on load flow, stability, voltage profile, system frequency and fault level studies which are also performed for normal operating conditions. For these studies, the modelling methods and the system parameters used in the restoration study are basically the same as that in the studies for normal system operating conditions.

However, with the extraordinary system configuration during restoration, the behaviour of the system is basically electromagnetic transient in nature and this requires some special electromagnetic transient analysis, and different system modelling methods and system parameter requirements. For example, for the analysis of the resonance over-voltage in restoration through transformers, it requires the modelling of the non-linear magnetizing characteristics of the transformers. It is therefore important to build appropriate models and use appropriate parameters according to the objectives of the studies.

III. RESONANCE OVER-VOLTAGE

A major concern during restoration is the resonance over-voltage occurred during the energization of a no-load transformer as shown in Fig. 1.

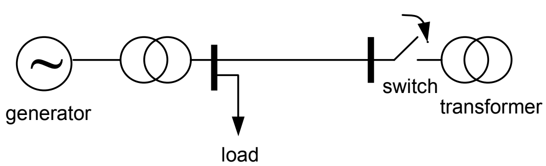

Fig. 1: Energizing a No-load Transformer

The root cause of resonance over-voltage is the unfavorable combination of the source impedance, the shunt capacitance of the energized circuits, the non-linear magnetizing characteristics of the energized transformer, inadequate damping of the system and the source voltage phase angle at the moment the transformer is energized.

Resonance over-voltage is not commonly known as it usually does not exist in normal operating condition. It is also not possible to identify its existence by common system analysis tools using linear models for system elements. Fig. 2 shows a typical waveform of resonance over-voltage recorded by site measurement.

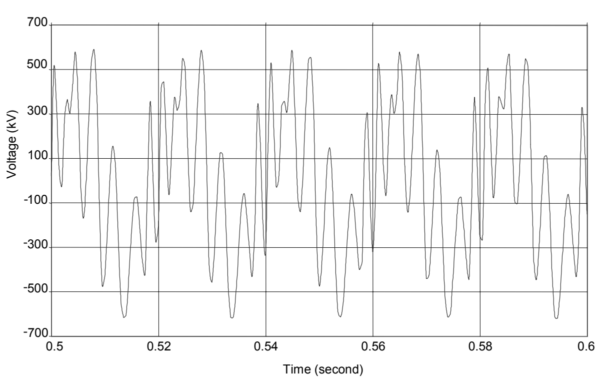

Fig. 2: Recorded waveform of Resonance Over-voltage

Resonance over-voltage is a kind of sustained or poorly damped temporary over-voltage. The waveform shown in Fig. 2 contains a number of high frequency harmonic components which can be identified by a Fourier analysis. The Fourier analysis result (as shown in Fig. 3) indicates that the dominant harmonic voltages components of the voltage waveform are in the range of 250-300Hz.

System equipment is usually designed to withstand a power frequency over-voltage of about 1.6 p.u. for one minute. The equipment can withstand higher over-voltage if the duration of the over-voltage is shorter. However, the magnitude of resonance over-voltage may exceed 1.6 p.u. for a longer time if the resonance is poorly or not damped.

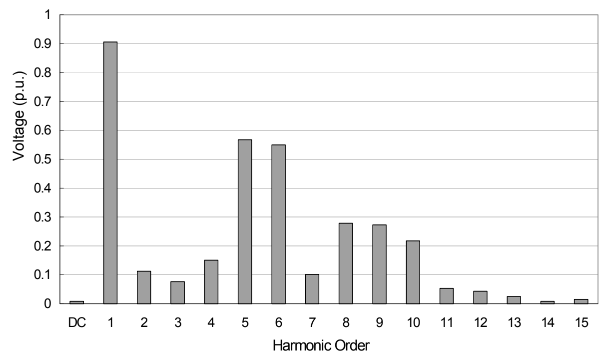

Fig. 3: Fourier Analysis of Resonance Over-voltage in figure 2

Furthermore, the protective devices in the system such as surge arresters will normally be activated before the resonance over-voltage reaches the equipment's over-voltage withstand limits. Also the over-voltage withstand capability of the equipment may deteriorate due to aging or other internal defects.

Therefore, sustained resonance over-voltage, even it is below the specified over-voltage withstand capability of system equipment, may damage the system equipment or result in tripping of some circuits during restoration process. Such situation is not desirable and the risk of resonance over-voltage should be minimized.

IV. APPROACH TO ASSESS THE RESONANCE OVER-VOLTAGE

The resonance over-voltage can be assessed either by performing computer simulation studies or by conducting field tests.

Simulation study has the advantage of being flexible to study all kinds of network configurations and system conditions. It can also be used to identify the causes of the resonance over-voltage and formulating remedial measures. As compared with field tests, simulation study itself would impose no risk to the equipment if resonance over-voltage exists. However, the trustworthy of the simulation results has to be supported by verification.

On the other hand, field tests can provide actual system response data and verify the simulation study results so as to prove the feasibility of the restoration plan. However, field tests require significant resources and can only be performed for limited combinations of system configuration and operating conditions. Field test may also impose some risks to the supply reliability and equipment safety if risk mitigation measures are not effective.

To take the advantages of both methods, i.e. computer simulation and field tests, CLP Power has adopted a hybrid approach to assess the resonance over-voltage during restoration process by conducting computer simulation studies and supplementing with selective field tests.

V. SIMULATION OF THE RESONANCE OVER-VOLTAGE

As mentioned above, computer programs using linearized system models are not capable to simulate the behaviour of the system with resonance over-voltages. The tools required for this task are mainly computer programs for analysis of electromagnetic transient phenomena. The effectiveness of such analysis also depends on appropriate modelling and use of parameters in the computer program.

Simulation study is conducted with the EMTP to assess the resonance over-voltage for a specific network arrangement. Carefully selected field tests are also conducted to calibrate the modelling methods and parameters used in the simulation study. For the case as shown in Fig. 1, it is found that the non-linear magnetizating characteristics of transformers have dominant effects in the simulation results and has to be included in the simulation models with data from the manufacturers. Fig. 4 is a typical B-H curves showing the non-linear characteristics of power transformers.

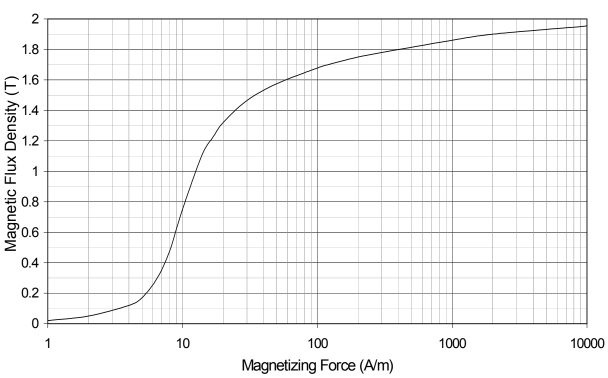

Fig. 4: A typical B-H curve of transformers

After calibration by selective field tests, the accuracy of the simulation models is observed to be improved. For example, with the calibrated model, the recorded resonance over-voltage in Fig. 2 is re-produced by a simulation. The simulation results are as shown in Fig. 5. The simulated waveform of the resonance over-voltage is almost identical to the recorded one.

Should linear magnetizing characteristics be assumed in the simulation model, no resonance over-voltage would have been identified by the simulation. The simulation results with a linear model in the EMTP are shown in Fig. 6. The voltage waveform is close to sinusoidal and does not reflect the resonance over-voltage as in the actual situation.

The modelling of other system parameters are also important to obtain an accurate results. For example, the shunt capacitance of the cable and overhead lines, the shunt reactors and capacitors, the loads and even the point of wave when the transformers are energized would all affect the simulation results. Without including the shunt capacitance of cables and overhead lines in the model, the resonance overvoltage would have a totally different waveform. The load also play an important part in simulation because the load can provide the necessary damping to the resonance overvoltage.

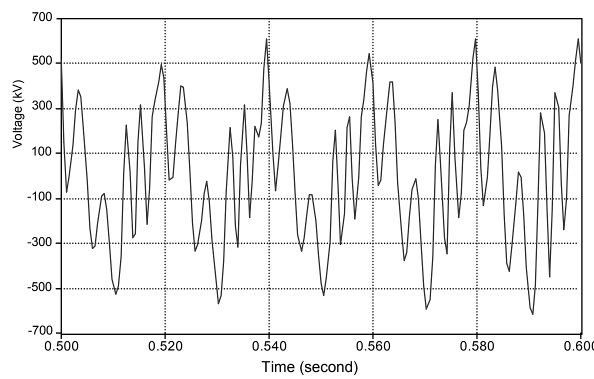

Fig. 5: Simulation Results – Reproduction of the recorded Resonance Over-voltage as compared with Fig. 2

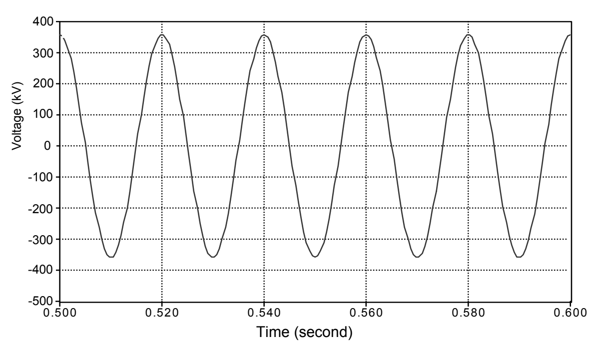

Fig. 6: Simulation Results – Using Linear Models in the EMTP

Using these calibrated models and parameters, the causes of the resonance over-voltage as well as the sensitivities of resonance over-voltage behaviour due to various system parameters can also be identified. It is concluded that the following factors contribute to a higher level of resonance over-voltage:

1. Higher rating of the transformer to be energized;

2. Lower value of source fault level;
3. Longer circuit length;
4. Smaller amount of load in the system;
5. Higher system voltage profile;
6. Higher working flux density of the transformer;
7. Transformer energized at the point near the maximum voltage.

Based on these findings, resonance over-voltage mitigation measures are then designed during the development of the restoration strategy. It is observed that by adopting one or more of the following measures, the resonance over-voltage can be effectively reduced to an acceptable level:

1. Large transformers are energized with larger or multiple generators
2. Carrying as much load as possible by the source before energizing a transformer
3. Selecting a short and hence low impedance path for energization of a transformer
4. Reducing the system voltage before energizing a transformer

For example, the resonance over-voltage as shown in Fig. 2 can be reduced by adopting the following measures:

1. Using a larger generating source (about 10 times)
2. Selecting circuits of higher voltage level
3. Carrying some load at the source before energizing the transformer

The simulation results are shown in Fig. 7 below. Compared to Fig. 2, the resonance over-voltage is greatly reduced to an acceptable level.

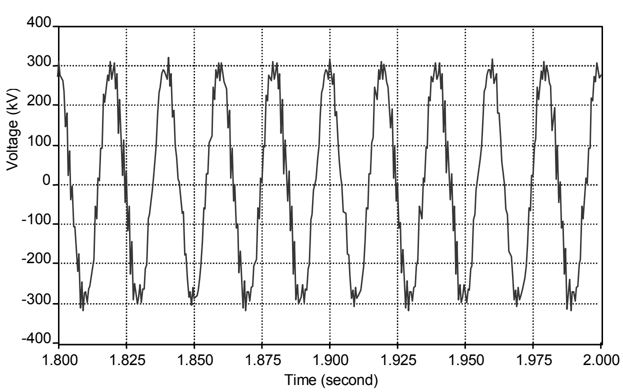

Fig. 7: Simulation Results – with Mitigation Measures for resonance over-voltage

VI. FIELD TESTS

Field tests are very useful and important in the resonance over-voltage studies. During the simulation studies, recorded field tests results are used to calibrate the simulation model and parameters. After the restoration strategy is developed, field tests are conducted for verification of the restoration plan formulated.

Although detailed studies and risk assessment have been conducted before the field tests, further precaution measures are designed as the last line of defense to protect the system equipment from being damaged by resonance over-voltages when they occurred.

Based on the temporary over-voltage withstand capability of various equipment involved in the field tests, over-voltage relays are installed at strategic points of the system under test with their protective settings coordinated with the most vulnerable equipment, i.e. surge arresters. If the actual resonance over-voltages are higher than the expected value obtained through simulation, the over-voltage relays will trip the circuits from the source before the surge arresters are activated.

The voltage waveform during the field tests are recorded and compared with the corresponding simulation results obtained before the field tests. One of the recorded voltage waveform is shown in Fig. 8. This field test has the identical system configuration as the simulation in Fig. 7. The two voltage waveforms are almost identical, further confirming the accuracy of the simulation model and the parameters used.

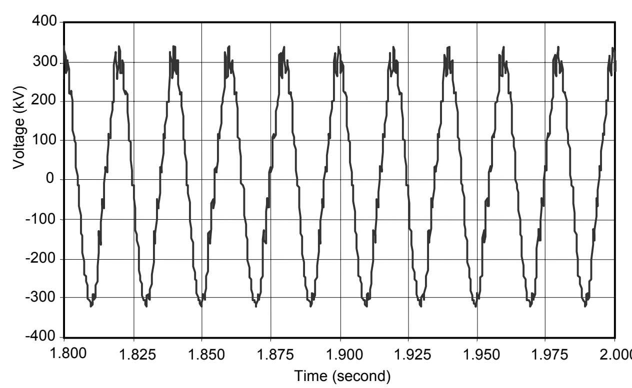

Fig. 8: Field Test Results – with Mitigation Measures

VII. CONCLUSION

Due to the non-linear and complex characteristics of the restoration studies, a wide range of issues should be assessed by different tools and modelling methods. For the resonance over-voltage study, the computer program to study the electromagnetic transient is an appropriate tool to simulate the non-linear magnetizing characteristics of the transformers. The study models and parameters are calibrated against the field test results to ensure its reliability and accuracy. Using these calibrated models, the causes and the sensitivities for the occurrence of resonance over-voltage with various system parameters can be identified. Furthermore, effectiveness of over-voltage mitigation measures, e.g. selection of appropriate generators, circuits and transformers, and load requirement for the energization configuration can be assessed.

It is a common practice for utilities to prepare energization procedure to effect fast restoration of supply to customers. With such approach, CLP Power is able to establish a full inventory of system restoration procedures with great confidence.

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REFERENCES

[1] Study Committee 38, Working Group 02, Task Force 02 (Modelling of abnormal conditions), "Modelling and Simulation of Black Start and Restoration of Electric Power Systems" Electra No. 147, pp. 21-42, 1993

[2] M. M. Adibi, R. W. Alexander and B. Avramovic, "Overvoltage Control During Restoration" IEEE Transactions on Power Systems, Vol. 7. No. 4, pp. 1464-1470, November 1992

[3] M. M. Adibi and L. H. Fink, "Power System Restoration Plan" IEEE Transactions on Power Systems, Vol. 9. No. 1, pp. 22-28, February 1994

[4] R. Yacamini and N. Hatziargyrious, "Overvoltage caused by blocking twelve pulse h.v.d.c. scheme" IEE Proceedings, Vol. 127, Pt. C, No. 3, May 1980