A TECHNICAL EXPERIENCE DURING NETWORK ASSET REPLACEMENT: INVESTIGATING CABLE AND TRANSFORMER SWITCHING INTERACTIONS

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ABSTRACT

This paper describes ferroresonant transients experienced by a 132/33kV transformer upon opening the upstream circuit breaker which is fed via a long cable. The transformer core is saturated by the cable discharging stored energy into it, resulting in oscillatory and transient voltages and currents at the transformer terminals. Field tests and computer simulations were conducted to aid the understanding of this phenomenon in order to rule out the possibility of causing insulation damage during switching operations in such a system configuration.

INTRODUCTION

Distribution network asset replacement program has been recently carried out in an increasing volume across the Europe, due to the fact that network infrastructures are ageing and reinforcing the aged infrastructure is becoming a necessity to ensure the reliable supply of electricity. When replacing aged equipment asset in a substation, it is necessary to keep in mind that design and manufacturing technologies have significantly changed in the last forty years. To replace aged equipment, sometimes an assumed like-for-like replacement may not necessarily be true or yield the same system performance, when considering interactions and compatibilities among equipment in a distribution system.

During commissioning of a newly reinforced 132/33kV substation, unusual audible noises were heard when de-energising the transformers. The initial assessment of the network configuration concluded that the noises were from core saturation and ferroresonance.

In the UK distribution network, a grid transformer tends to be operated by the circuit breaker in the upstream substation and a fair length of cable or overhead line is connected in between. De-energising a transformer with a long cable connected to it can induce the occurrence of ferroresonance transients due to the interaction between the cable and the transformer.

Ferroresonance is an old topic and there are substantially large volumes of literature studying this practical phenomenon experienced by transmission & distribution networks upon state-changing events such as switching or fault operations [1-3]. Not only are overvoltages and overcurrents experienced by transformers during ferroresonance, but also overfluxing can occur, and the associated local overheating is regarded as one of the long-term ageing factors [4].

Switching ferroresonant transients is not specified in standard factory tests – it is system configuration related and not necessarily experienced by all power transformers, and therefore transformers can not be tested before acceptance and commissioning. Depending on individual transformer design, some transformers may be able to withstand ferroresonance and the associated energy dumped into the transformer without causing localized overheating, whereas the others may not.

It is therefore of interest for an utility to understand the cause, the impact and the mitigation measure of ferroresonant transients when de-energising transformers, in order to understand/reduce associated ageing/failure risk.

Taking advantage of a planned outage at another 132/33kV substation which has the same configuration, switching operations were scheduled and tests were recorded.

In this paper we report cable-transformer interaction events found during de-energisation operations in a typical 132/33kV UK distribution network configuration. Switching ferroresonant transients were studied via field tests and computer simulations in the aim to help understanding this phenomenon.

DISTRIBUTION NETWORK LAYOUT AND DE-ENERGISATION TEST EVENTS

Distribution network layout

The relevant part of distribution network for de-energising a 132/33kV grid transformer includes: in the upstream substation busbar, circuit breaker, isolator, earth switch & the cable and in the downstream substation including earth switch, isolator, earth switch, grid transformer, auxiliary transformer, a short length cable, VT and circuit breaker. The circuit arrangement is given in Figure 1.

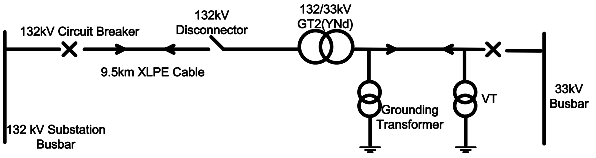


Figure 1 Distribution network diagram–relevant parts

During normal switching events – the opening sequence of circuit breakers is such that the 33kV circuit breaker is opened first to shed the load, and the 132kV circuit breaker is then opened to de-energise the off-load transformer. However in such a network configuration where the transformer is fed via a long cable it tends to saturate when the cable discharges itself through transformer core impedance.

Field investigative tests

The newly commissioned grid transformers were manufactured in 2007 and the feeding cable length is 11.5km.-, On the other hand, the field test substation has transformers manufactured in 1997, fed by cables of 9.5km. Both are single core XLPE cables.Four switching operations were carried out on two 132/33kV transformers, upon de-energisation audible noise was heard from the transformer although lasting for a short time period.

This confirmed that ferroresonant transients are commonly associated with transformers in such a network configuration.

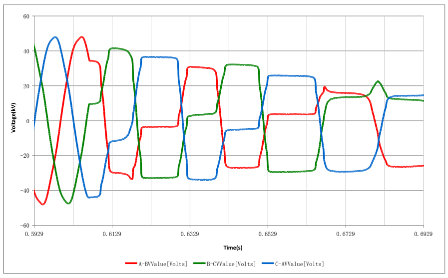
As well as recording voltage and current waveforms, acoustic sensors designed for partial discharge detection and location were used to pick up the unusual audible noise and pin-point if the source location can be localized. During this investigative field test oil samples were taken before and after the tests for DGA analysis.

Transformer voltage and current waveforms upon de-energisation

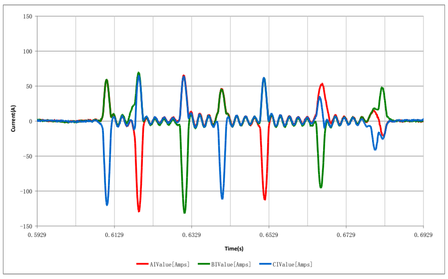
The voltages and currents of the 132/33kV 90MVA transformer were recorded via the protection VTs and CTs using a transient recorder. The three-phase 132kV line currents and 33kV line voltages were recorded. The transient recorder has sampling frequency f_s = 12.8kS/s and the recording length of data is set for 2.4s.

After de-energisation, the transformer voltage and current waveforms seen were oscillatory and transient in nature. The whole transient process lasts for less than 0.62s. The voltage has a square like waveform, and the current oscillates between positive and negative spiky high magnitude.

Four sets of test results were obtained, which can be divided into two types of ferroresonant waveform pattern. Type 1, as shown in Figure 2, is such that the saturation starts at/near to the negative voltage peak of one phase and the three-phase ferroresonant current magnitudes during core saturation follow 1:-0.5:-0.5 ratio. Type 2, as shown in Figure 3, the saturation starts at/near to the positive voltage peak of one phase and the peak magnitude of three-phase ferroresonant currents during core saturation occurred with some time delays and do not follow 1:-0.5:-0.5 ratio. Among the total four records, three belong to Type 2.

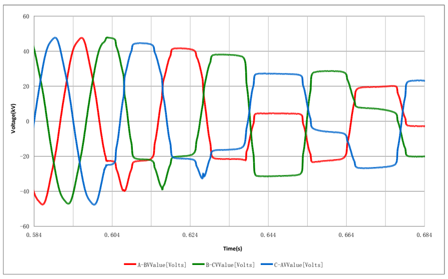


(a) Secondary side line voltages-recorded

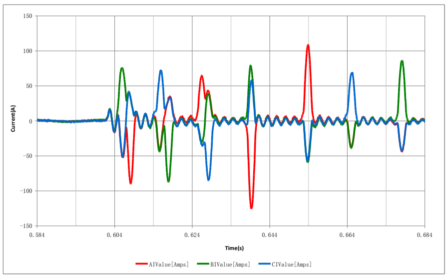


(b) Primary side line currents-recorded

Figure 2 Type 1 ferroresonant transient waveforms



(a) Secondary side line voltages - recorded



(b) Primary side line currents -recorded

Figure 3 Type 2 ferroresonant transient waveforms

COMPUTER SIMULATIONS

Transient simulation model in ATP

The circuit shown in Figure 1 can be represented in ATP to include the main components of the 132 kV voltage source, circuit breaker, cable and grid transformer, whereas the connected auxiliary transformer, 33kV cable and 33kV VT are further neglected. The simplified circuit is shown in Figure 4. The internal impedance of 132 kV voltage source is obtained from the substation three phase fault level data. The busbar ground capacitance is included in parallel with the downstream circuit including the CB ideal switch model, the cable model and the transformer model. They are modeled using factory test results and design data given in the appendix.

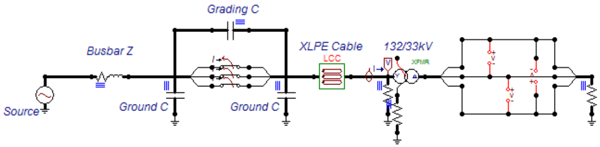


Figure 4 Circuit representation and modeling in ATP

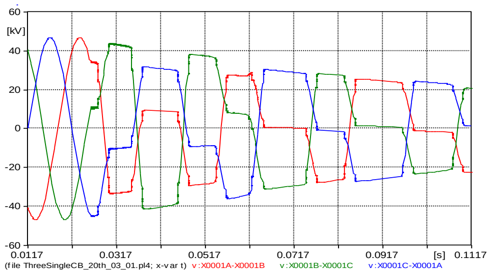
Simulation results

Type 1 ferroresonant transients can be simulated by controlling the circuit breaker switching time and current chopping magnitude. When the first phase current is chopped at 10A and the other two phases opened subsequently in about 1ms intervals, type 1 ferroresonant transients can be simulated and the simulation results can be found in Figure 5. The simulation results are similar to those in Figure 2, in voltage and current magnitudes, except the oscillating frequencies are slightly higher. The three-phase saturation magnetising currents follow the magnitude ratio of 1:-0.5:-0.5 which correspond to the singular change of voltage waveforms.

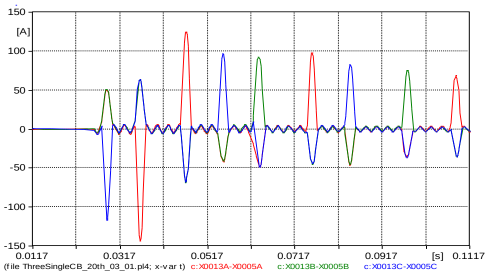
For Type 2 ferroresonant transients, the circuit breaker is controlled in such a way that the first phase current is chopped at 10A and after 1ms the other two phases of the circuit breaker are opened simultaneously. The simulated results can be found in Figure 6. They are similar to those in Figure 3, in voltage and current magnitudes, except the oscillating frequencies are slightly higher. Type 2 saturation magnetising currents have two spiky current pulses which correspond to the triangular voltage waveforms.

Energy dumped into transformer during ferroresonant transients

From the previous field recorded results and simulation analysis, it is clear that the unusual noise heard when de-energising the off-load transformer is due to core saturation and ferroresonance. However detailed analysis indicates that there is no overvoltage on the transformer terminals and the highest saturation magnetising current is about 130A, which is much higher than the normal magnetising current (I_m=0.98A) but less than the full load current (I_L=396A).

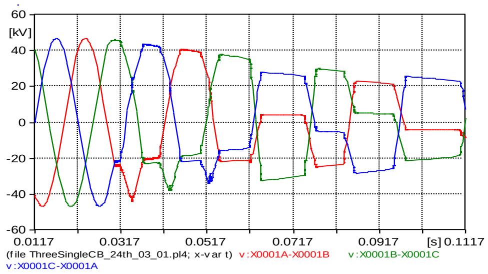


(a) Secondary side line voltages-simulated

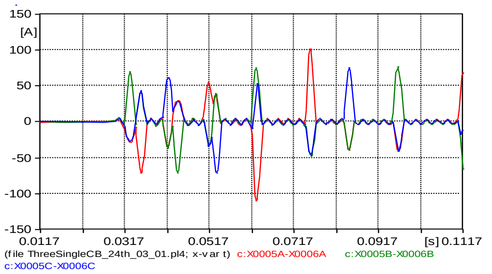


(b) Primary side line currents-simulated

Figure 5 Type 1 ferroresonant transient waveforms



(a) Secondary side line voltages-simulated



(b) Primary side line currents-simulated

Figure 6 Type 2 ferroresonant transient waveforms

The potential damage of this ferroresonant transient phenomenon is therefore not caused by overvoltage or overcurrent, instead it can be due to the fact that the flux was forced to go through other paths as well as the core. Overfluxing and its side effects of producing induced eddy currents and local heat concentration can be a long-term ageing factor. However the total energy dumped into the transformer during the short last time of transient (t=0.62s) is only 50kJ, which is higher than no-load loss but much lower than load-loss. From this comparison it seems reasonable to conclude that the heating effect may not be significant due to the transient nature of ferroresonance upon de-energisation, because the dumped energy is not highly concentrated.

OTHER INVESTIGATIONS

In terms of overfluxing and flux jumps, they are likely to occur near to the core joints. During the investigative field tests acoustic sensors from Physical Acoustics Ltd were used to locate the source of the audible noise. However the acoustic emission from the de-energisation event is relatively low and the acoustic emission did not hit enough sensors to allow a 3D location.

The DGA analysis on the oil samples was normal, and there was no trace increase of any overheating gases in the oil samples taken before and after the tests.

CONCLUSIONS

During normal de-energisation events, interaction between the circuit breaker, cable and transformer in this distribution network configuration results in a ferroresonant transient phenomenon. In nature, the transient ferroresonance is due to the fact that the energy stored in the cable capacitance discharges itself via the transformer core inductance and causes core saturation. Since the energy source (cable capacitance) is a limited one, the ferroresonance will not be sustained. Depending on the coordination of three-phase switching time of the circuit breaker, fine differences can exist on ferroresonant voltage and current waveforms.

Overall no overvoltages were seen on field tested transformers, high magnitude spiky ferroresonant currents were experienced by the transformer for less than 1s and the total energy dumped into the transformer is about 50kJ, much lower than load loss. The monitoring of acoustic signals did not provide sufficient information to pinpoint the source of the noise in the transformer. The results of the oil sample analysis did not indicate that there had been any deterioration in the components of the transformer.

This investigation was carried out on transformers fed via 132kV polymeric cables, which have a high capacitance. Since this phenomenon was recognized, similar audible noises have been detected in transformers fed via overhead lines and oil assisted cables. In all cases the transformer is switched from the source substation, with no local circuit breaker.

For sustained ferroresonance is recognized as a long term ageing factor for power transformers, without solid evidence to rule out the possibility of ageing and to be totally conservative, utilities might consider the following at the substation design stage as: (a) whether to include local circuit breakers and (b) whether to include requirements in the transformer specifications to cover for the effects of transient ferroresonance.

ACKNOWLEDGEMENT

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APPENDIX

Table 1 Dimension of Single Core XLPE Cable

Parameter	Value (mm)
Diameter of conductor	21.5
Thickness of Conductor screen	0.8
Thickness of insulation	19.0
Thickness of core screen	1.0
Thickness of Semicon WST	1.0
Thickness of lead sheath	3.5
Thickness of Bitumen	0.5
Thickness of MDPE sheath	3.65

Table 2 No Load Loss Test Data

%	Line Voltage (RMS) (V)	Voltage (Measured) (V)	Average Phase Current (A)	Loss (Measured) (kW)
90	29732	29702	0.64	23.63
100	33037	33005	0.98	29.67
110	36320	36296	1.81	37.65

Table 3 Zero Sequence Impedance

Voltage (V)	Current (A)	Ohms per Phase (ohm)	Temp (℃)	% Impedance
1538.9	119.29	38.70	20	19.99

Table 4 Load Loss and Positive Sequence Impedance

Line Impedance Voltage (V)	Average Line Current (A)	Power (MVA)	% Impedance Measured	Measured Loss (kW)
29628	378.1	90	23.37	279.9