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Vector space representation of signals for transient signal analysis in transformers and shunt reactor

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ABSTRACT

During the impulse testing of power apparatus, there were failures which are better visible in time domain spectrum of the measured transient signals (applied impulse voltage and responses of the apparatus) while others in frequency domain. Hence, testing engineer needs to utilize time or frequency domain spectrum or combination of both to make a final decision about the power apparatus. In this paper, the principles of vector space representation of signals are effectively adopted in the measured transient signals during the impulse testing of transformers and shunt reactor. It provides a better way to visualize the mutual computation between the measured transient signals through proper adoption of projection theorem, normalization and orthogonal matrix principles.

In this context, the normalized transient signal due to reduced impulse voltage is considered to be first basis function. The next successive impulse sequences of the transient signals due to rated impulse test voltage are made mutually orthogonal to previous transient signals through projection theorem. The constructed orthogonal signal is normalized for formulation of orthonormalized basis signal. If the surge characteristic of the winding is changed due to faults during the rated impulse test voltage, then the mutual effective coefficient needs to identify the deviation based on 'best mutual matches' between orthonormalized basis signal and first basis function. The mutual effective coefficient makes a 'best mutual matches' through appropriate mathematical formulation to provide the occurrence or non-occurrence of faults. To express the performance of the mutual effective coefficient, 5 MVA, 7.5 MVA, 150 MVA transformers, 80 Mvar shunt reactor and 22 kV interleaved disc winding are considered.

1. Introduction

The transformer and reactor are one of the most important equipments playing a major role in a power system network. The shunt reactor is employed in the power system network to improve the system stability and energy efficiency of transmission by directly connecting it to the power line or to a tertiary winding of a three-winding transformer. Depending on the load pattern of a long high voltage transmission lines and balance of reactive power, the shunt reactors are positioned in a parallel configuration to compensate for the capacitive currents common to long transmission lines or power cables. Especially, great care has to be exercised to guarantee that the transformer and shunt reactor are not damaged due to the lightning. Hence, to assess the ability of transformer and shunt reactor for withstanding the lightning in service, lightning impulse test is performed at high voltage test laboratory by Marx's generator.

Lightning impulse test is a dielectric test after assembly of transformer and shunt reactor. The details about the connections, tolerance on applied impulse waveshapes, principle for waveshape control, voltage levels and correction factors are specified in International Electrotechnical Commission (IEC) and Institute of Electrical and Electronics Engineers (IEEE) standards [1–3]. In addition, the impulse test is generally performed only with rated full wave (FW) voltages. In special cases, a FW and chopped impulse wave (CW) can be additionally agreed upon with the customer. The information on application requirements of impulse test sequence (presence and absence of CW with FW) is a well established procedure and the interpretation of impulse test results are also presented in IEC and IEEE standards [1–3]. Hence, impulse test involves excitation of FW and CW in a standard sequences to ascertain the integrity of the winding insulation of transformer and shunt reactor.

IEC and IEEE standards also provide the guidelines to identify the failure based on the comparison of the measured applied impulse

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Table 1
Technical specifications of transformers and shunt reactor.

Specifications	Transformer 1	Transformer 2	Transformer 3	Shunt reactor
Power rating (MVA)	5	7.5	90/120/150	80 Mvar
Voltage rating (kV) HV/LV/TV	66/11	33/6.9	220/34.5/4.16	420
Frequency (Hz)	50	50	60	50
Phase	3	3	3	3
Vector group	Dyn11	Dyn1	YNyn0d5	Star
Standard	IS 2026	IS 2026	IEEE C57.12.00	IEC 60076
BIL (kV)	HVL-325, LVL-95, LVN-95	HVL-170, LVL-95, LVN-95	HVL-900, HVN-900, LVL-250, LVN-250, TV-75	L-1300, N-550
Applied waveshape	Negative polarity with FW	Negative polarity with FW	Negative polarity with FW and CW	Negative polarity with FW and CW

voltages and winding responses (current signal) between reduced full wave voltage (RFW) and FW voltages or between successive measurement at FW voltage [2,3]. The final assessment of the transformer must always be based on its performance in accordance with all the impulse test sequences as per the specified standard in the technical specification and late of course in service. Generally, the visual assessments of the oscillographic traces in time domain are performed to declare the pass or fail criteria of the power apparatus during the impulse test. In addition, the identification of failure through the visual examination of the oscillographic traces of applied impulse voltages and winding responses is not trivial [4] and to some extent remains subjective [5]. Hence, the reliable technique for sensitive detection of fault in the transformer and shunt reactor during the impulse test is necessary for power industries. In this paper, vector space representation of signals are used to identify the fault in the transformers and shunt reactor based on digital manner of recording the impulse voltage and current signal during the impulse test [6].

2. Measurement of transient signals during impulse test

As per the technical specifications (Table 1), the transformers and shunt reactor are subjected to standard sequences of impulse test voltage with the specified wave shape of 1.2/50 μs using 2.2 MV, 80 kJ impulse voltage generator (HIGHVOLT-GMBH, made in Germany). If the impulse voltage is applied to high voltage (HV) line terminal (R, Y, B terminal for 3 phases) of any winding (HV winding or low voltage winding, LV), then impulse wave will propagate along the turns and sections of the windings and finally reach the end of the winding. The responses of the winding (winding current or transient signal) due to short duration of applied impulse voltage waveshape (transient signal) are recorded by measuring the voltage across the standard low resistance shunt using neutral current method [7]. In neutral current method, a measurement of winding current passing through a resistive shunt between neutral and the ground point is used effectively to identify the fault [1–3]. The winding response consists of a high frequency oscillation, a low frequency disturbance and a current rise due to reflections from the ground end of the windings. The non tested winding terminals are grounded through standard or known resistance shunt or grounded directly [2,3,7,8].

The measured windings responses would be strongly dependent on both electromagnetic and capacitive mutual coupling between the turns, intersections of the winding and type and nature of winding. In addition, the applied impulse voltage waveshape on HV line terminal of the transformer causes the appearance of a winding response at the winding terminal. The measured applied impulse voltage waveshape and winding response (winding characteristic) forms the basic building blocks to identify the fault. Therefore, the applied voltage waveshape and winding responses record are of sufficient duration of time interval to permit detection of any discrepancies (fault) occurring late in time. Here, the measured transient signal data are function of time (t) over a finite interval.

The digital impulse measurement of the transient signals allows the testing engineer to analyze the wide range of digital signal processing tools (signal/vector space representation of signals) into high voltage test data analysis (breakdown and partial discharge) than mere visual examination of oscillographic traces. Hence, if the fast digital signal recorders are employed for extraction of concrete information from the raw data of the transient signals, a numerical method of waveform analysis is achievable to detect the insulation failure of power apparatus. Hence, with the availability of signal recorder of 14 bit, MIA 100–14/4B, 100 M sample/s, one channel of a signal recorder with a HV divider is connected to the input terminal of the transformer in order to get the applied impulse voltage waveshape digitally. The winding response, generally the current to ground of the opposite terminal of the excited winding, is connected to the other channel of the signal recorder using a shunt resistor.

3. De-noising methods for analysis of transient signal

In practice, due to the presence of noise in the measured transient signals, it is difficult to detect the fault directly (visually) inspecting the difference between signals. Hence, the identification of sophisticated digital filtering methods will be useful to detect the fault before using any fault detection technique.

3.1. Wavelet multivariate de-noising method for analysis of transient signals in time domain

Generally, wavelet transform is a multi-resolution method to process the transient and non-stationary or time varying signals [9–11]. The effectiveness of the wavelet transform depends on the selection of mother wavelet and an adequate threshold of the detailed wavelet coefficients. A number of different wavelet transforms have been utilized effectively [9–11]. The main three steps of wavelet de-noising approach are selection of wavelet, decomposition of signal and threshold selection.

In recent studies, the combination of wavelet transforms and principal component analysis in multivariate de-noising method has been formulated [12] and used effectively to locate the partial discharge (PD) in transformers using UHF method [13]. In this paper, multivariate de-noising method is utilized to remove the noise in the measured signals. Hence, the experimentally measured signals are passed through the multivariate de-noising method. For example, Figs. 1 and 2 show de-noised time domain responses of HV winding of 5 MVA and 7.5 MVA transformer (R phase)

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