New approach towards Very Fast Transients suppression

W. Piasecki, G. Bywalec, M. Florkowski, M. Fulczyk and J. Furgał

Abstract –Very high frequency components in the power networks pose a risk to the electrical equipment as they can destroy motors, transformers and other electrical equipment due to internal resonant phenomena resulting in local amplification of voltage. Overstressing the insulation system reduces significantly the equipment lifetime and often leads to internal short-circuit.

In the present article a new approach towards suppressing VFTs with the use of a compact series impedance element is presented. The approach developed enables one to construct a compact protective device introducing a series impedance upstream in the protected equipment. The device is particularly suitable for protecting transformers connected to low loss cable lines with the use of a Vacuum Circuit Breaker (VCB).

Experiments have shown that the use of the series impedance element enables one to efficiently suppress overvoltages and HF oscillations associated with the switching operations.

Keywords: VFT, protection, vacuum circuit breaker, cable line, wave reflection, oscillation, medium voltage, transformers, motors .

I. INTRODUCTION

Electrical power networks are subjected to various forms of electrical transients. The transients can be classified in various ways depending on their origin, amplitude, or frequency spectrum. They can often disturb the operation of electrical equipment or, in extreme cases, can cause equipment damage. The low frequency transients are generally well understood and appropriate mitigation methods are known. The influence of the high frequency transients (characterized by frequencies extending over the MHz region) influence on the electrical equipment however, is not obvious, as small construction or material details can significantly affect the character of internal phenomena. Therefore in many cases, understanding the HF behavior of a power network device often requires an elaborated case-by-case investigation.

II. HF TRANSIENT NETWORK PHENOMENA

The HF components in the power network may result from statistical events such as lightning surges and switching or fault transients [1-4]. An analysis of these transients is fundamental for equipment troubleshooting, and for designing or improving the electrical system protection.

Very Fast Transients (VFT) can destroy motors, transformers and other electrical equipment due to complicated internal phenomena resulting in local amplification of voltage [5]. Overstressing the insulation system reduces significantly the equipment lifetime and often leads to internal short-circuit. Of special concern is electrical equipment with dry type insulation. In particular dry transformers and motors, especially those supplied by Variable Speed Drives should be carefully protected against the accelerated insulation aging process resulting from overvoltages combined with high dU/dt rates.

The statistics of transformer failures provided by IEEE [6] indicates that in the case of 23 % of failures the root cause could not be clearly identified. The CIGRE A2-A3-B3.21 joint working group refers to these numbers in [7] and suggests that also the failures categorized as electrical-design related (10 %) and material-related (17 %) may in fact result from Very Fast Transient.

The use of Vacuum Circuit Breakers (VCB) which became predominant in MV networks in combination with short (~100 m) or moderate length (~500 m) low-loss cables results in multiple VFT phenomena taking place during contact making or breaking of the switch.

There are known methods of preventing the excessive exposure of the equipment to the VFTs. Practical aspects of their applicability as well as their limitations will be discussed further.

III. CONFIGURATIONS OF SPECIAL CONCERN

VFT phenomena posing risk to transformers are associated with the events of switching operations with the use of VCBs. An additional important factor of concern is the way the network components are interconnected. The use of low-loss cable lines (especially XPLE) of moderate length (several tens of meters to several hundreds of meters) are generally regarded as the important risk factors [7]. The HF phenomena posing risks of overstressing the insulation systems may take place both during the contact making and the contact breaking of the interrupter.

They are in particular related to:

1. Switching off an unloaded transformer having the natural frequency sufficiently high to result in fast Transient Recovery Voltage (TRV) build-up and potential re-ignitions in the VCB. This concerns especially transformers of at least several MVA. An example of EMTP-simulated switching off an unloaded 2.5 MVA, 15 kV transformer is shown in Fig. 1. In the simulations the way of modeling the VCB behavior enabling re-strikes, described in the references [8], [9] was used.

Presented at the International Conference on Power Systems Transients (IPST'07) in Lyon, France on June 4-7, 2007

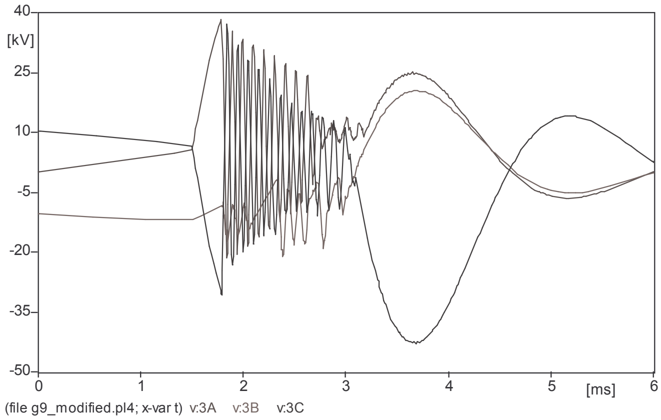

Fig. 1.Simulated switching off a 2.5MVA transformer. Individual traces correspond to the phase-to-ground voltages at the transformer terminals

2. Switching on a transformer to a high-capacitance network (e.g. local cable network of a wind farm).

If the cable connections are short, the speed of the input capacitance charging from the network capacitance is limited in practice only by the line resistance and the value of the phase-to-ground capacitance of the transformer.

For longer connections, when the wave properties of the lines become visible, the wave impedance of the line Z_L, rather than just the line resistance in combination with the input capacitance (phase-to-ground), determines the speed of the voltage build-up. In the case of the typical cable lines the value of the wave impedance is of the range of 20 -30 Ω, which combined with a typical value of a phase-to-ground capacitance C_0 of the range of single nF result in the risetime:

$$\tau = \left|Z_L\right| \cdot C_0 \tag{1}$$

of the range of tens of nanoseconds.

Moreover, the HF impedance mismatch between the transformer (Z_T) and the line (Z_L) result in potential wave reflections, multiplying the overvoltage build-up at the transformer terminals, as the wave reflection coefficient is described by a well-known formula:

$$\Gamma = \frac{Z_T - Z_L}{Z_T + Z_L} \tag{2}$$

An example of the simulated VFTs during connecting a transformer to a 100m XPLE line is shown in Fig. 2 (delays of 0.5ms between contact closings in individual phases were assumed). In the simulations a simple switch model was used, therefore effects such as pre-strikes or contacts re-bouncing were not taken into account.

The potential pre-strikes in the VCB during the contact making process result in complex transient HF phenomena. The real time-based evolution of voltages and currents at the device terminals during a specific event of switching is a result of a combination of multiple factors. Some of them depend on the network parameters, which can be determined. Some of them however, are of statistical nature and therefore the exact match between the simulation result and a specific experimental observation is very difficult. Nevertheless, some characteristic features of the waveforms, such as typical overvoltage levels, voltage risetime value, oscillations frequency and characteristic decay time for a properly modeled system should match the experimental values.

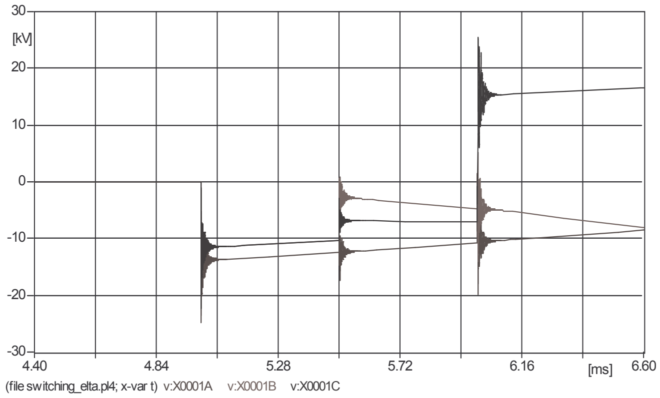

Fig. 2. Simulated VFT during connecting a transformer (250 kVA transformer) to a 100 m long XPLE line. Individual traces correspond to the phase-to-ground voltages at the transformer terminals

IV. KNOWN METHODS OF PREVENTING THE VFT-RELATED RISKS TO TRANSFORMERS

The recommended practice to install a surge protection package containing of three phase capacitors and three surge arresters is presented in the references [10], [11]. This typical method of preventing VFT is based on introducing an additional capacitance which combined with the line series impedance (or wave impedance) forms a low pass filter. The surge capacitors are widely manufactured for standard voltage levels beginning from 1 kV to 30 kV. The typical capacitance range is at least several hundreds of nF. This large value of the capacitance results from the fact that the series impedance of the cable is very low.

Such big a capacitance is a serious load for the network and may cause problem during energizing of the circuit (inrush current).

Surge capacitors also form two resonant circuits. The first one, formed with the impedance of the load, may result in hazards due to overvoltages generated by self oscillating circuit during deenrgetization of the load. The second resonant circuit, which may also potentially generate overvoltages, is formed with the impedance of the connecting cable.

Surge capacitors do not solve the problem of proper wave termination of the cable as for high frequencies the end of the line is shorted-circuited.

To avoid same of these problems often additional resistors are connected in series with surge capacitors, forming an RC snubber. The role of the resistor is i) to reduce the inrush capacitive current and ii) to provide a wave termination at the end of the cable. Therefore the typical recommended value of the series resistance is several tens of ohms, which matches the wave impedance of the typical MV cables (see TABLE 1).

It is important to note that the wave termination function is fulfilled, however only if the HF impedance of the equipment is high (the HF impedance at the end of the line is a parallel connection of the snubber impedance and the equipment impedance). This is often not true as power equipment for frequencies above several hundredths of kHz may be represented as a capacitance of several nF.

TABLE I
WAVE IMPEDENCE OF TYPICAL MEDIUM VOLTAGE CABLES FOR DIFFERENT NOMINALL CURRENT CABLES (VALUES CALCULATED ON THE BASIS ON THE PHYSICAL DATA)

Inom	A	87	147	210	317	413	556
S	mm^2	10	25	50	95	150	240
L/100m	µH	38,4	33,6	30,6	27,7	26,1	25
C/100m	µF	17	23	27	37	45	54
Zw	Ω	**47,5**	**38,2**	**33,7**	**27,4**	**24,1**	**21,5**

Large value of the snubber capacitance results in capacitive currents imposing high power requirements on the resistors.

The size and cost of installation of RC snubbers is therefore significant and thus they are rarely used in practice, especially for protecting small transformers.

V. NEW APPROACH TOWARDS VFT SUPPRESION

Main problem in avoiding the VFTs is a low value of the series impedance of power cables and proper termination of the end of the cable. Increasing the impedance of the line may be achieved by introducing an additional series element upstream the equipment. The use of magnetic rings placed around the cable was explored for this purpose [12]. The evaluation of various HF magnetic materials concludes in difficulties in achieving the required impedance value already at frequencies well below 1 MHz and in avoiding the saturation of the magnetic material with the load currents.

In the method proposed in the present article a series impedance element (choke) is installed upstream the protected device (transformer). The R - L choke of appropriately designed frequency characteristic allows one to overcome the drawbacks of the former concepts. Additionally, in the present concept the series impedance element (choke) is complemented with a small capacitor connected phase-to-ground as shown in Fig. 3. In order to provide the VFT suppression functionality, and at the same time to have a negligible effect during normal operating conditions, the following objectives must be fulfilled:

- the choke should represent a significant impedance (preferably of a resistive character) already at frequencies well below 1 MHz (or even 100 kHz, as internal resonances in transformer may exist at these frequencies),
- the choke must not be saturated with the load current,
- the series element (choke) should be transparent at 50 Hz
- the voltage drop across the element at 50 Hz must be very low.

Additionally, in order to be applicable for protecting small transformers the complete device should be compact and low-cost, not significantly influencing the price of the transformer or motor.

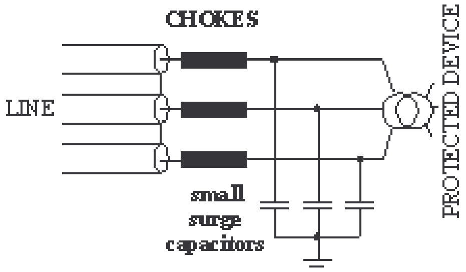

Fig. 3. VFT protection circuit

Meeting the above requirements enables one to suppress or eliminate various types of hazardous effects associated with the switching operations. Therefore the expected functionality is as follows:

- reduction of dU/dt (resistive character of the choke combined wit the capacitor forms an integrating circuit)
- limiting the overvoltage level
- eliminating wave reflections (at high frequencies the line is terminated with the impedance of the choke)
- eliminating re-strikes due to limiting of the transient recovery voltage (TRV) build-up speed.

A device fulfilling the objectives defined was designed as a combination of an inductive and a resistive component. The values of the inductance and of the resistance were selected so that the stable series impedance value of ~ 30 Ω is achieved already below 100 kHz.

The stable value of the series impedance element matches a typical value of the wave impedance of a MV cable line. Therefore for higher frequencies (>1 MHz), at which the wave propagation effect must be taken into account the end of the line is terminated with a series connection of the impedance of the choke (Z_{SC}) and a high frequency impedance of the capacitor $Z_C=1/j\omega C$ connected in parallel with the surge impedance of the transformer. If the capacitance value is only 10 nF, as opposed to the several hundreds nanofarrads recommended for the typical snubber circuits, the value of Zc is < 15 Ω for frequencies above 1 MHz. Therefore already for the C value as low as 10 nF the wave termination of the cable line is achieved and the reflections are minimized.

For lower frequencies, for which the wave impedance does not play a role the presence of the choke element introduces a series impedance upstream the transformer equipped with a small surge capacitor. Thanks to the presence of the series impedance of the choke, an integrating circuit is created upstream the transformer, reducing significantly the dU/dt values.

VI. PHYSICAL REALIZATION

A set of the new VFT suppressing devices (1 unit per each transformer phase) was designed according to the requirements described before. The chokes installed at the terminals of 10kV dry-transformer windings are shown in Fig. 4. The frequency dependence of the choke impedance is shown in Fig.5.

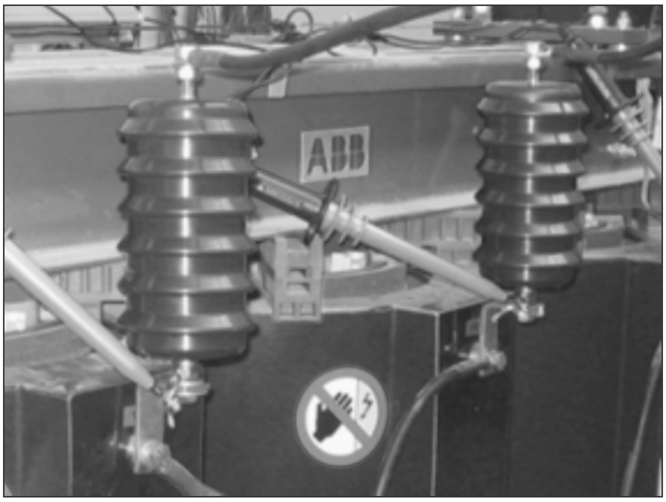

Fig. 4. VFT suppressing chokes installed on a dry type distribution transformer (surge capacitor not presented).

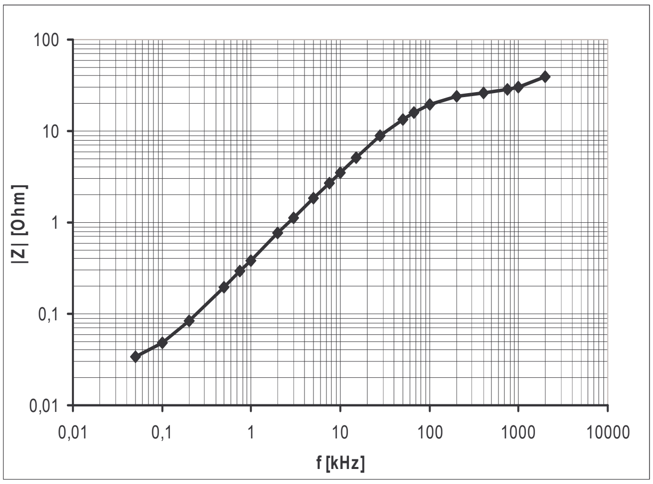

Fig. 5. Frequency characteristic of the series choke (measured)

VII. EXPERIMENTAL VERIFICATION

The ability of the new device to suppress the VFTs was experimentally verified on a realistic set-up, comprising a 630 kVA, 10 kV dry transformer. The transformer was connected to a short cable line (3, single phase 30 m/phase EPR cables) with a VCB. The MV source at the end of the cable was backed-up by a capacitor bank (3 x 10 nF). The diagram of the experimental set-up is shown in Fig. 6.

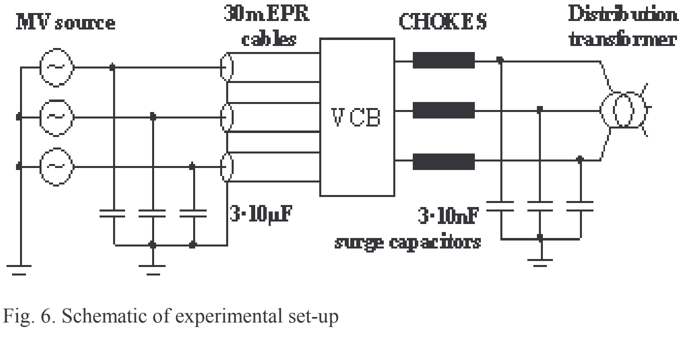

Fig. 6. Schematic of experimental set-up

The experiment involved a series of connecting and disconnecting the unloaded transformer with the VCB. The high-speed digital recording was performed using a set of high frequency (50 MHz) probes (1000 x) and a TEKTRONIX DPO 4054 oscilloscope.

VIII. RESULTS

As a reference, number of recordings were performed for an unprotected transformer. The results were repeatable and always contained characteristic HF components. A typical waveform pattern observed during the contact making process is shown in Fig. 7.

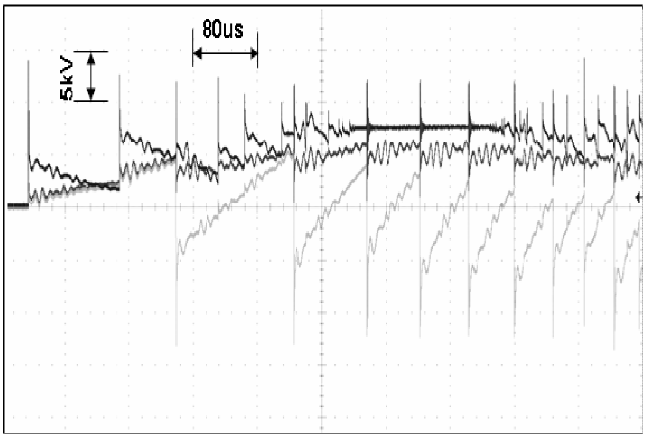

Fig. 7. A typical patterns of phase-to-ground voltages recorded during contact making process (transformer not protected). The total record length 0.8 ms

Multiple HF transients can be observed resulting from pre-strikes in the vacuum chamber. Each of the pre-strikes results in the HF overvoltage characterized by a high dU/dt value. Detailed analysis of the wavefronts revealed the risetimes valueas of the order of 100 ns, at the overvoltage factors up to 2 p.u. Additionally, the voltage steps are followed by HF oscillations. A corresponding picture for the transformer protected with the new device developed is shown in Fig. 8.

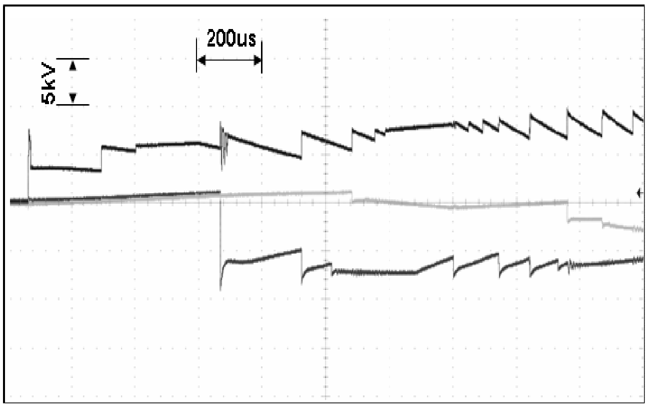

Fig. 8. A typical pattern of phase-to-ground voltages recorded during contact making process (transformer protected). The total record length 2 ms

One can clearly see the HF overvoltages and the oscillations are practically eliminated. Detailed analysis of the wavefronts at the pre-strikes reveals a significant change in the dU/dt, as shown in Fig. 9.

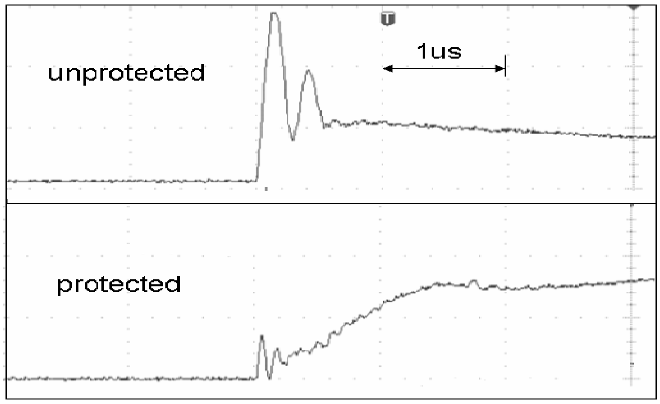

Fig. 9. Expanded view of the wavefronts of one of voltage steps typical for connecting the transformer to line

During the disconnecting of the unloaded transformer multiple re-strikes were observed in the case when the transformer was directly connected to the VCB (the unprotected transformer case). A typical wave pattern is shown in Fig. 10.

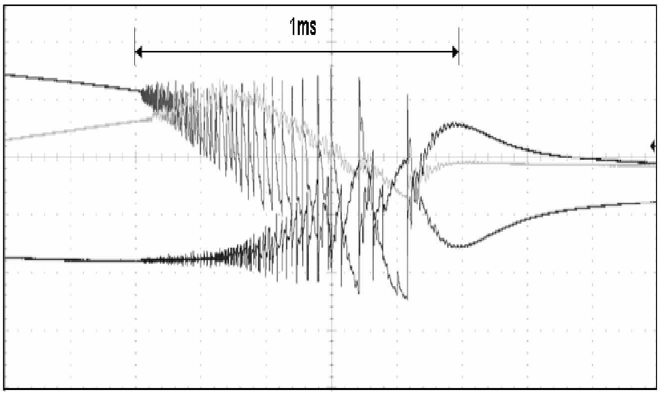

Fig. 10. A typical pattern of phase-to-ground voltages recorded during contact breaking process (transformer not protected)

Protecting the transformer with the set of chokes and capacitors resulted in practically eliminating the re-strikes, as shown in Fig.11.

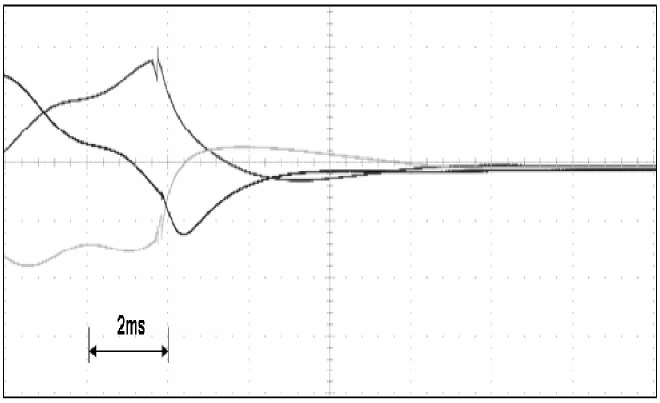

Fig. 11. Eliminating the re-strikes and the corresponding HF transients during the contact breaking process by the set of chokes and capacitors connected

IX. CONCLUSIONS

The HF components in the power network resulting from interactions between the individual network components can pose risks to the insulation system of transformers and other electrical equipment. The switching operations with the use of VCBs may result in HF transient phenomena which in some configurations may result in high overvoltage levels and, at the same time, in high dU/dt values. Known methods of protecting the equipment are rarely used for protecting distribution transformers due to economy reasons.

The new method described is based on introducing a frequency-dependent series impedance element (choke) upstream the protected device in combination with a small surge capacitor. I was demonstrated that the present approach allows one to build a compact, low-cost protecting device. Experimental evidence proved the applicability of the device for efficiently suppressing the VFTs associated with the switching events with the use of a VCB.

X. REFERENCES

[1] J. P. Bickford, A. G. Heaton, “Transient Overvoltages on Power Systems”, *IEE Proceedings,* Vol. 133, Pt. C, No. 4, May 1986, pp. 201-223

[2] J. Lopez –Roldan, H. de Herdt, J. Min, R. van Velthove, J. Decklerq, T. Sels, J. Karas, D. van Dommelen, M. Popow, L. van der Sluis, M. Aquado, “Study of interraction between distribution transformer and vacuum circuit breaker”, *13th Int. Symp. on High Voltage Engineering ISH’2003,* Delft (Holland), 25-29 August 2003, pp. 62

[3] R. B. Lastra, M. Barbieri, “Fast Transients in the Operation of an Induction Motor with Vacuum Switches”, *Int. Conf. on Power Systems Transients IPST’2001*, 24-28 June 2001, Rio de Janeiro (Brasil), paper 063

[4] D. Dufournet, G. F. Montillet, “Transient recovery voltages requirements for system source fault interrupting by small generator circuit breakers” *IEEE Trans. on Power Delivery*, Vol. 17, No. 2, April 2002, pp. 474-478

[5] A. S. Morched, L. Marti, R. H. Brierly, J. G. Lackey, “Analysis of Internal Winding Stresses in EHV Generator Set-Up Transformer Failures”, *IEEE Trans. on Power Delivery,* Vol. 11, No. 2, April 1996, pp. 888 - 894

[6] IEEE Guide for reporting failure data for Power Transformers, 1986

[7] CIGRE working group A2-A3-B3.21, “Electrical Environment of Transformers; Impact of fast transients”, ELECTRA 208, February 2005

[8] S. M. Wong, L. A. Snider, E. W. Loi, “Overvoltages and reignition

behavior of vacuum circuit breaker" *Int. Conf. on Power Systems Transients IPST'2003*, 28 September - 2 October 2003, New Orleans (USA), paper 14a.3

[9] M. Popov, E. Acha, "Overvoltages due to switching off an unloaded transformer with a vacuum circuit breaker", *IEEE Trans. on Power Delivery*, Vol. 14, No. 4, October 1999, pp. 1317-1322

[10] IEEE Std 242-2001^{TM} "Recommendation Practice for Protection Coordination of Industial and Commercial Power System"

[11] IEEE Std C37.96-2000 "IEEE Guide for AC Motor Protection"

[12] L. Weidong, X. Zhuato, Q. Jiali, "Simulation Tests of Suppressing VFT in GIS by Magnetic Rings" , *14th Int. Symp. on High Voltage Engineering ISH'2005,* Beijing, China, 25-29 August 2005, J-51

XI. BIOGRAPHIES

Wojciech Piasecki was born on May 15,1966 in Poland. He received his MSc. in Electronics from the University of Science and Technology Cracow, Poland) and a PhD from the Jagiellonian Univeristy (Cracow, Poland). He has been working for many years in the area of electromagnetic and electrical phenomena, including high frequency and non-linear modeling of electrical equipment. Currently a researcher at the Corporate Research Center in Cracow. His main activity concentrated around transient network phenomena analysis

Jakub Furgał graduated from the AGH University of Science and Technology in Krakow (Poland). He received M. Sc. and Ph. D. degrees in electrical science in 1980 and 1988 respectively. He works in the Electrical Power Institute at the AGH University of Science and Technology in Krakow.

His research interests include overvoltage protection issues and power transformers diagnostic methods.

Marek Florkowski was born on July 3, 1965 in Cracow Poland. He received his M.S. and Ph.D degrees in Electronics from the University of Science and Technology (AGH) in Cracow in 1990 and 1994, respectively. From 1990 to 1992 he was employed at ABB Corporate Research Center in Baden-Dättwil, Switzerland. Currently he is responsible for ABB Corporate Research Center in Cracow, Poland. He is a member of IEEE and CIGRE.

Marek Fulczyk was born in 1968 in Poland. He received the M.Sc. and Ph.D. degree in Electrical Engineering from the Wroclaw University of Technology/Poland in 1993 and 1997, respectively. In 1997 he joined ABB as a research scientist. Now he is a group leader of Electrical & Engineering Systems at ABB Corporate Research in Cracow, Poland. His fields of interests include power system protection, power system/voltage stability, real-time collaborative technology, 3D modelling and simulations of phenomena in power systems.

Grzgorz Bywalec was born in Oświęcim in Poland, on Fegruary 10, 1979. He received his MSc. in Electronics from the University of Science and Technology (AGH) in Cracow, Poland. He joined ABB Corporate Research Center in Cracow in 2006. His research interest concentrates around electromagnetic modeling of power equipment.