

New General Method for Differential Protection of Phase Shifting Transformers

Z. Gajic, *Member, IEEE* I. Ivankovic, B. Filipovic-Grcic, R. Rubesa

Abstract — 400MVA, 400/220kV Phase Shifting Transformer is in full commercial operation in Zerjavinec Substation since July 2004. Since then, a few external faults happened which has been used to check proper behavior of existing transformer differential protection relays. At the same time the disturbance records from these faults has been used to successfully test a new possibility for differential protection of such transformer. By using these records it has been shown that, with numerical technology, it is feasible to use dynamic, on-line phase angle shift compensation for differential protection of phase shifting transformers.

Index Terms - Phase shifting transformers, Power transformers, Power transformer differential protection, Protective relaying.

I. NOMENCLATURE

PST – Phase Shifting Transformer,
OLTC – On-Load Tap-Changer
OHL – Overhead Line

II. INTRODUCTION

THE first phase shifting transformer in the Croatian Power System has been in successful operation since July 2004. Its construction is quite simple [3], [9]. It is constructed as an autotransformer with an OLTC with twenty-five positions in the neutral point. By an off-load switch, located between the tap winding in the neutral point and the common autotransformer winding, it is possible to change the individual phase sequence connections between these two windings. Thus, the operating mode of the power transformer can be changed from the autotransformer to the PST.

This PST interconnects 400kV and 220kV power networks in the northwestern region of HEP grid. The PST has regulation facility of only $+6,8^\circ$ to $-4,5^\circ$. This corresponds to approximate additional injection of +150MW, respectively –120MW between 400kV and 220kV power networks.

Operating experience with this PST is very good [5]. Its operation has strengthened the whole

surrounding HEP network. Different operating scenarios, during last two years, have proven its usefulness for entire HEP power system. During some operating condition PST was loaded up to 90% of its rating. Its presence, allows network operator to control active power flow in HEP grid in accordance with actual operating conditions, such as agreed international active power transit across HEP system, outages of other elements in surrounding network etc.

III. EXISTING PST RELAY PROTECTION SCHEME

In accordance with HEP protection philosophy for 400kV power system objects, the PST is protected with two numerical, multifunctional relays from different manufacturers. The complete PST protection scheme is shown in [9].

A. Existing PST Differential Protections

The existing differential protection functions within two relays are arranged in the same way as for a conventional autotransformer. Thus, they are only connected to the stand-alone 400kV and 220kV CTs as shown in [9]. It shall be noted that the power transformer tertiary delta winding is not loaded and it is only used as stabilizing delta winding [7]. However, due to this delta winding, the zero sequence currents from the 400kV and the 220kV sides must be always excluded from the differential current calculations.

As per standard protection practice, these two differential relays have been set to be ideally balanced for the power transformer OLTC mid-tap position. The power transformer name-plate in the PST mode of operation is given in [9].

B. Main 1 Differential Protection Features

The Main 1 (i.e. M1 in further text) differential relay [2] has the unique but standard features, which makes it superior for this particular PST application:

- 1) on-line OLTC position reading
- 2) four setting groups
- 3) bias current is common for all three phases and it is selected as highest measured current.

The first feature enables the M1 differential relay to automatically compensate for power transformer turn-ratio changes caused by OLTC operation. However, this relay is capable only to compensate for current magnitude variations caused by OLTC movement. The relay is not able to compensate for non-standard phase angle shift (i.e. different from 0°) caused by OLTC

Z. Gajic is with ABB Power Technologies AB, Substation Automation, Vasteras, Sweden (e-mail: zoran.gajic@se.abb.com).

I. Ivankovic, B. Filipovic-Grcic and R. Rubesa is with the HEP–Croatian Transmission System Operator, Kupka 4, 10000 Zagreb, Croatia (e-mail: igor.ivankovic@hep.hr, bozidar.filipovic-grcic@hep.hr and renata.rubesa@hep.hr).

operation in PST operating mode. The OLTC position is read via BCD coded binary signal.

The second feature was used to automatically change the M1 relay setting group depending on the power transformer off-load switch position [3]. This change is necessary in order to cope with power transformer different turns ratio in autotransformer and PST operating modes.

The third differential relay feature, about common bias current, is usefully because for this PST application it was calculated that the maximum false differential currents during external earth faults can be actually obtained in two healthy phases [4], [5].

For two-winding power transformer, the M1 differential relay utilizes the following matrix equation to calculate the differential currents in percents of the power transformer rating:

$$\begin{bmatrix} Id_L1 \\ Id_L2 \\ Id_L3 \end{bmatrix} = \frac{100}{I_{b400}} \cdot F \cdot \begin{bmatrix} I400_L1 \\ I400_L2 \\ I400_L3 \end{bmatrix} + \frac{100}{I_{b220}} \cdot H \cdot \begin{bmatrix} I220_L1 \\ I220_L2 \\ I220_L3 \end{bmatrix} \quad (1)$$

where:

- Id_L1 is differential current in phase L1 in %
- $I400_L1$ is 400kV, phase L1 primary current in A
- $I220_L1$ is 220kV, phase L1 primary current in A
- I_{b400} is base current on 400kV side and it has different value for every OLTC position as shown in [9] (column four of Table I in [9]). This actually provides current magnitude compensation for differential protection due to OLTC movement.
- I_{b220} is base current on 220kV side and it has fixed value of 999,7A as shown in [9] (column six of Table I in [9])
- F and H are three-by-three matrices used to provide zero-sequence current reduction and phase shift compensation for each winding respectively

For this particular installation HEP has ordered three-winding power transformer differential relay. Into the differential relay the following rated power transformer data were entered: 400/400/130MVA; 400/231/10.5kV; Yy0d5. Thus, the M1 relay has automatically selected the following F and H matrices:

$$F = H = \frac{1}{\sqrt{3}} \cdot \begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ 1 & 0 & -1 \end{bmatrix} = \begin{bmatrix} -0.5774 & 0.5774 & 0.0000 \\ 0.0000 & -0.5774 & 0.5774 \\ 0.5774 & 0.0000 & -0.5774 \end{bmatrix} \quad (2)$$

Such solution is identical with traditionally used solutions with analogue transformer differential relays where y/d connected interposing CTs were used in autotransformer differential protection schemes. By using equations (1) and (2) it is now possible to recalculate the differential currents as seen by M1 differential relay from the captured disturbance recording files in Žerjavinec substation.

IV. NEW POSSIBILITIES FOR PST PROTECTION

Reference [6] introduces a generalized normalization matrix transformation $G(\Theta)$, which can be used to calculate matrices F and H from equation (1) for any standard power transformer phase angle shift. According to [6], this transformation has the following form:

$$G(\Theta) = \cos(\Theta) \cdot U + \sin(\Theta) \cdot J \quad (3)$$

where Θ is required phase angle shift, while U and J are three-by-three matrices, which have the following values for the three phase power system:

$$U = \frac{1}{3} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \quad (4)$$

$$J = \frac{1}{\sqrt{3}} \cdot \begin{bmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{bmatrix} \quad (5)$$

The question was raised can this transformation be used for PST differential protection? Simply, one can try to dynamically change F and H matrix coefficients, in equation (1), for every new PST OLTC position. If this would be feasible, the dynamic, on-line phase angle shift compensation can be achieved in a similar way as already used current magnitude compensation.

It was found out that it is possible to use at least two combinations of different F and H matrix element values, which can completely fulfill this task. The first combination is:

$$F = G(0^\circ) \text{ \& } H = G(-\Theta_{12}) \quad (6)$$

and the second combination is:

$$F = G(\Theta_{12}) \text{ \& } H = G(0^\circ) \quad (7)$$

where Θ_{12} represents the angle for which 220kV side no-load voltage leads the 400kV side no-load voltage. This is the standard way in which PST phase angle shift is defined in accordance with international standard [8]. This angle has different values for every OLTC position, and for PST in Žerjavinec substation, these values are given in [9] (column nine of Table I in [9]).

Thus, it seems to be fully feasible to provide on-line compensation for actual PST phase angle shift due to OLTC movement. The new, improved method to calculate differential currents for this PST is expressed by using the following equation:

$$\begin{bmatrix} Id_{L1} \\ Id_{L2} \\ Id_{L3} \end{bmatrix} = \frac{100}{I_{b400}} \cdot G(0^\circ) \cdot \begin{bmatrix} I_{400_L1} \\ I_{400_L2} \\ I_{400_L3} \end{bmatrix} + \frac{100}{I_{b220}} \cdot G(-\Theta_{12}) \cdot \begin{bmatrix} I_{220_L1} \\ I_{220_L2} \\ I_{220_L3} \end{bmatrix} \quad (8)$$

By using equation (8) to calculate the PST differential currents, it is feasible to have practically zero differential currents during all through-load and external fault operating conditions, irrespective of the actual PST OLTC position. The only pre-request is that values for I_{b400} and Θ_{12} are dynamically changed in accordance with the actual OLTC position, and that $G(-\Theta_{12})$ matrix transformation is calculated on-line. In rest of the paper equation (8) will be used.

V. EVALUATION OF CAPTURED DR FILES

Numerous disturbance records have been captured during external faults and normal through-load conditions in this PST installation. Overview about this part of HEP grid and locations of three external faults, presented in this paper, are shown in Figure 1.

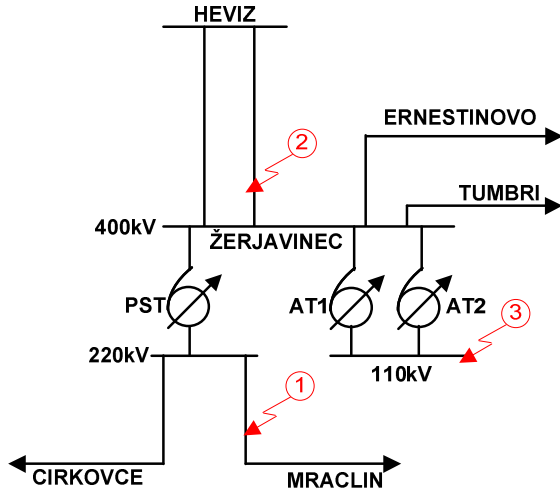


Fig. 1. Location of external faults around Žerjavinec Substation

Table I gives overview about all three DR files, captured during these external faults. The respective PST OLTC positions and some other relevant information are given as well.

TABLE I
SUMMARY ABOUT CAPTURED DR FILES

	Type of captured DR file		
	Ext. Fault #1	Ext. Fault #2	Ext. Fault #3
Type of Fault	L1-N	L2-N	L2L3-N
Fault Position	Mraclin OHL	Heviz 1 OHL	110kV Busbar
OLTC Position	25	18	13
Θ_{12}	$6,76^\circ$	$2,55^\circ$	0°
I_{b400}	555,2	565,3	577,4
I_{b220}	999,7	999,7	999,7

Table II gives overview about used $G(\Theta)$ values, calculated as per equation (3), which are necessary to calculate the new differential currents by using equation (8), for presented DR files.

TABLE II
SUMMARY ABOUT USED $G(\Theta)$ VALUES

Θ_{12}	$G(-\Theta_{12})$
$6,76^\circ$	$\begin{bmatrix} 0,6620 & -0,2631 & -0,3990 \\ -0,3990 & 0,6620 & -0,2631 \\ -0,2631 & -0,3990 & 0,6620 \end{bmatrix}$
$2,55^\circ$	$\begin{bmatrix} 0,6660 & -0,3073 & -0,3587 \\ -0,3587 & 0,6660 & -0,3073 \\ -0,3073 & -0,3587 & 0,6660 \end{bmatrix}$
0°	$\begin{bmatrix} 0,6667 & -0,3333 & -0,3333 \\ -0,3333 & 0,6667 & -0,3333 \\ -0,3333 & -0,3333 & 0,6667 \end{bmatrix}$

In the Figures 2, 3 and 4 captured DR files during external faults are presented. The following five traces are given for every case:

- 1) 400kV current waveforms
- 2) 220kV current waveforms
- 3) Differential currents as seen by existing M1 differential relay (i.e. by using (1) & (2))
- 4) Differential currents in accordance with new method (i.e. by using equation (8))
- 5) Phase angle difference between positive and respectively negative sequence currents from the two PST sides.

The DR files have been as well captured at the moment of the PST OLTC position change. Figure 5 gives info about new differential protection method behavior during OLTC position change. Number one in Figure 6 indicates time instant of PST OLTC tapping from position 16 to position 15. Number 2 in the same figure indicates time instant when new differential method adapts internal compensation to values which correspond to tap position 15. Differential currents fail back to zero as soon as correct compensation values are used.

By careful examinations of Figures 2 to Figure 5 it is possible to conclude the following:

- 1) Existing M1 differential protection measures up to 43% false differential current during close by single phase to earth faults. However, the through-fault current is quite high, up to 600%, and the M1 differential relay remains stable due to its restraining characteristic
- 2) New differential method calculates practically zero differential currents during all external faults and normal through-load conditions

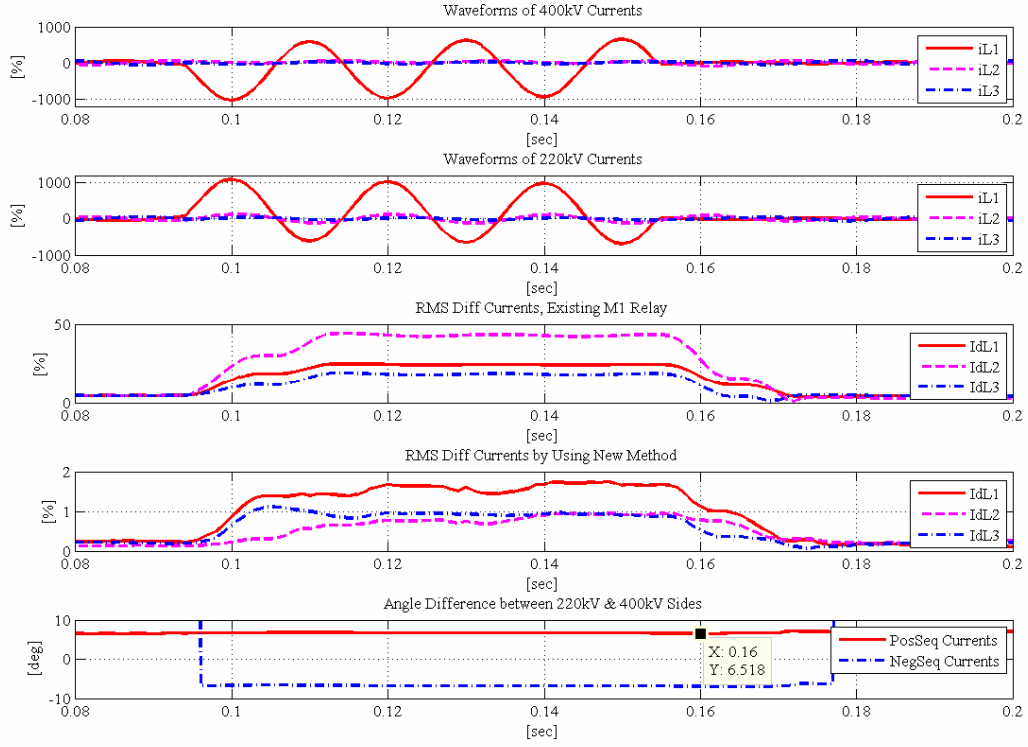


Fig. 2. External Fault #1, OHL Mraclin

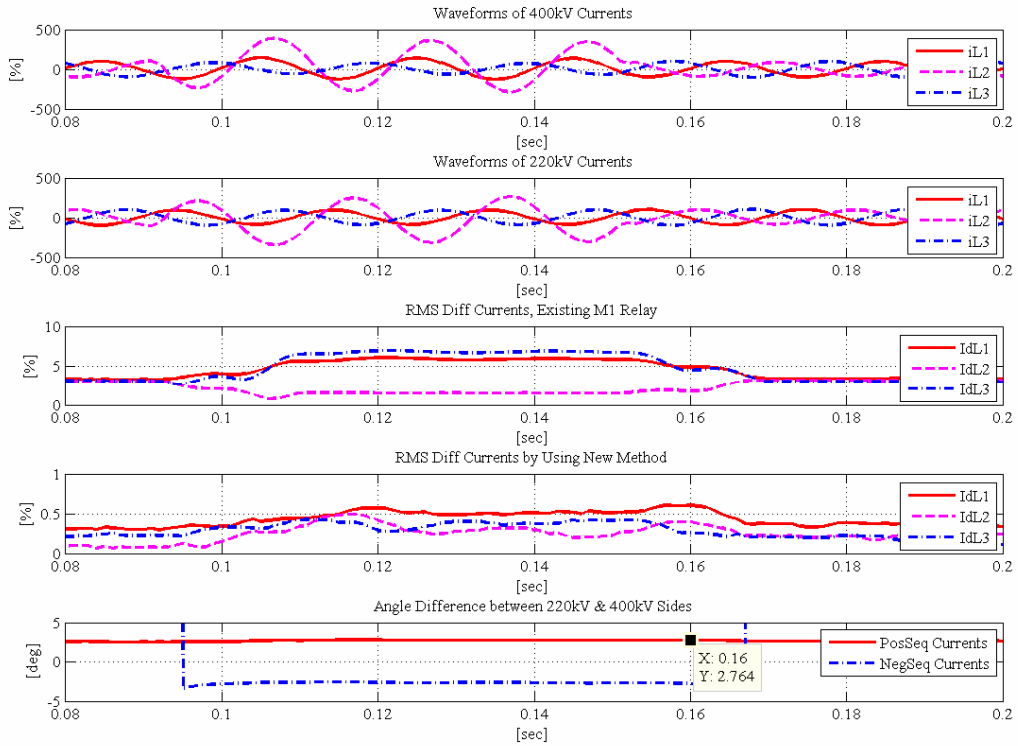


Fig. 3. External Fault #2, OHL Heviz 1

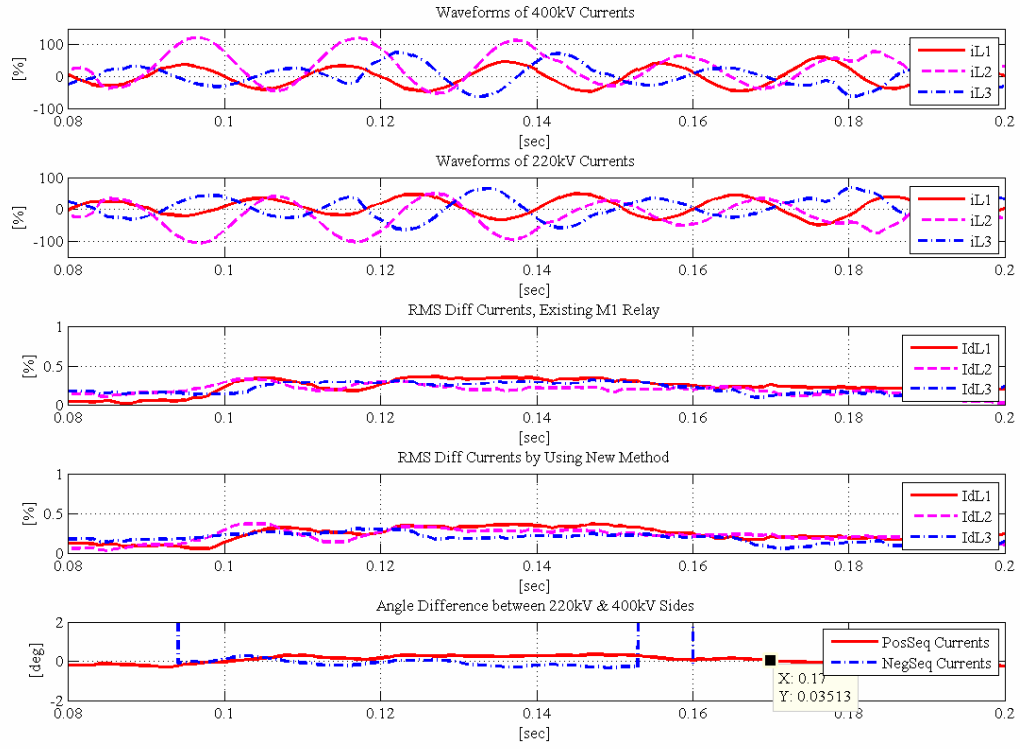


Fig. 4. External Fault #3 in 110kV Busbar

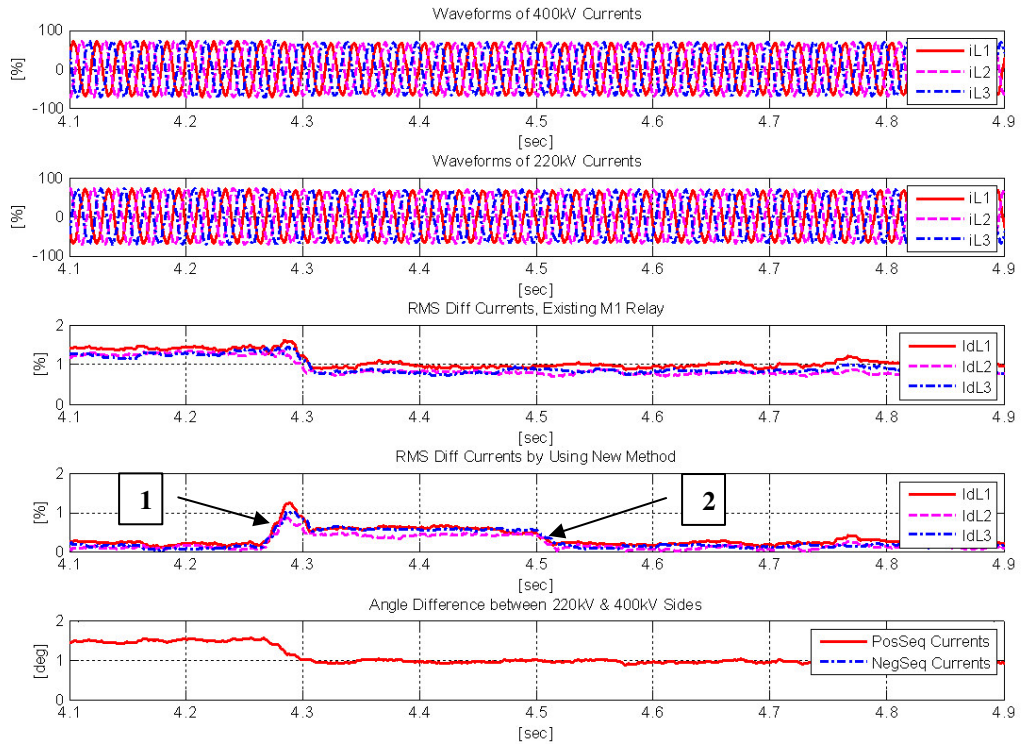


Fig. 5. Moment of OLTC position change from position 16 to position 15

- 3) Phase angle difference between 220kV and 400kV positive sequence currents is always equal to Θ_{12} value
- 4) During external non-symmetrical faults, the phase angle difference between 220kV and 400kV negative sequence currents is always equal to $-\Theta_{12}$ value

VI. CONCLUSION

The on-line reading of OLTC position and dynamic, on-line compensation of power transformer turns ratio is well-established protection practice [2]. It has shown excellent track record and it is de-facto industry standard in many countries. In this paper is shown, that it is feasible to go one-step further and provide dynamic, on-line compensation for PST non-standard and variable phase angle shift. By doing so, simple but effective differential protection for PSTs can be achieved.

Such differential protection is actually exactly the same as already well-established numerical differential protection for standard power transformers as shown in equation (1). The only difference is that F and H matrix element numerical values shall not be fixed, but instead they shall be calculated on-line. However, they can be calculated inside of the relay with quite slow cyclicity e.g. once per second. This practically should not pose any additional burden for modern numerical protections.

In practice, one OLTC step typically means PST phase angle shift change by one to two degrees. Therefore the required change of F and H matrix element numerical values are quite small, as shown in Table II. Thus, transition in differential current calculations between two OLTC positions is done smoothly as shown in Figure 5.

Authors have checked this new differential method on a number of disturbance files and simulation cases and it has been found out that this method always behaves correctly.

Furthermore, it was confirmed that the strict rules do exist for transferring positive and negative sequence currents across transformers and PSTs [1]. This can be effectively used to check load flow and short-circuit calculation results from different software packages for power system analyses when they are used for power networks with installed power transformers and PSTs.

VII. REFERENCES

- [1] *Electrical Transmission and Distribution Reference Book*, 4th edition, Westinghouse Electric Corporation, East Pittsburgh, PA 1950, pp. 44–60.
- [2] ABB Document 1MRK 504 021-UEN, "Application Manual, RET 521*2.3", ABB Automation Technology Products AB, Västerås, Sweden.
- [3] Z. Gajić, I. Ivanković, B. Filipović-Grčić, "Differential Protection Issues for Combined Autotransformer – Phase Shifting Transformer," *IEEE Conference on Developments in Power System Protection*, Amsterdam, Netherlands, April 2004.
- [4] I. Ivanković, B. Filipović-Grčić, Z. Gajić, "Zaštita Transformatora s Kombiniranom Uzdužnom i Poprečnom Regulacijom u TS Žerjavinec", 6. Savjetovanje HO CIGRÉ, Cavtat, Hrvatska, 9.-13. studeni 2003, (in Croatian language)
- [5] B. Filipović-Grčić, I. Ivanković, Z. Gajić, "Pogonska iskustva s diferencijalnom zaštitom transformatora s poprečnom regulacijom", 7. Savjetovanje HO CIGRÉ, Cavtat, Hrvatska, 6.-10. studeni 2005, (in Croatian language)
- [6] J.A.B. Elston, ABB, *Methods and Apparatus for Differential Current Measurement in a three-phase power system*, U.S. Patent 6,507,184; 2003-01-14.
- [7] *Power transformer*, International Standard IEC 60076, First edition 1997-10.
- [8] *Guide for the application, specification, and testing of phase-shifting transformers*, International Standard IEC 62032/IEEE C57.135, First edition 2005-03.
- [9] Z. Gajić, I. Ivanković, B. Filipović-Grčić, R. Rubeša: New Method for Differential Protection of Phase Shifting Transformers, Proceedings of the 15th International conference on Power System Protection, Bled, Slovenia, September 6-8, 2006, pp 220-227

VIII. BIOGRAPHIES



Zoran Gajić (M'95) was born in Serbia in 1965. He received his Diploma Engineer Degree with honors in electrical power engineering from University of Belgrade, Serbia in 1990 and Graduate Diploma in Engineering in computer engineering from Witwatersrand University, Johannesburg, South Africa in 1995. Currently he is a part-time, post-graduate student at Lund University, Sweden where he is pursuing the PhD Degree.

Since 1993 he has been working in the area of power system protection and control within ABB Group of companies, where he had various engineering positions. Currently he has a position of Application Senior Specialist with ABB Power Technologies AB, Substation Automation in Vasteras, Sweden. Zoran is a member of Cigré and PES/IEEE. Presently he is the convener for Cigré, Study Committee B5, WG16 "Modern Techniques for Protecting Busbars in HV Networks". He has published numerous technical papers in the relay protection area. His main working areas are practical applications of protection relays, computer applications for protection and control of electrical power system, development of advanced protection algorithms for numerical relays and power system simulations. Zoran is holder of four patents.



Igor Ivanković was born in Croatia in 1965. He received his Diploma Engineer Degree and Master of Science Degree from University of Zagreb, Croatia in 1991 and 2005 respectively. He was with Croatian Railway Company and Končar Company. Since 1995 he has been working with HEP-Transmission System Operator. He is CIGRÉ member and national B5 chairman.



Božidar Filipović-Grčić was born in 1946 in Croatia. He received the Diploma Engineer and M. Sc. degrees from the University of Zagreb, Croatia in 1971 and 1982, respectively. From 1971 he was with the HEP and Institute for Energy Zagreb. He was heading the Power System Protection Department. From 1989 to 2004 he was with HEP-TSO, as manager of Transmission area Zagreb. He was Secretary of Croatian Cigré Study Committee B5 and regular member of Cigré SC B5.



Renata Rubeša was born in Croatia in 1982. She received the Diploma Engineer Degree from University in Zagreb in 2005. Since her graduation she has been working in the area of relay protection with the HEP – Transmission System Company. Currently she is attending the Post Graduate Program at the Faculty of Electrical Engineering and Computing in Zagreb. She is cooperating as associate assistant at the University of Rijeka, Faculty of Engineering.