Modeling of IPC Transformer Windings for Fast Transient Studies

S.M.H. Hosseini, M. Vakilian and G.B. Gharehpetian

Abstract – The power flow within AC network can be controlled by the Inter-phase Power Controller (IPC). This controller acts as a dependent current source in such a way that the amplitude of current source output depends on the terminal voltage on the opposite side of the IPC. The control can be applied on the active and reactive power by variation of its suceptances.

During Fast Transient Over voltages (FTO), due to lightning, switching and the other disturbances, the probability of internal resonances within the transformer windings increases. This phenomenon can lead to very large over voltages along the windings that will endanger its insulation. At the critical condition, amplitude of these over voltages rise to some multiples of the lightning over voltages, and consequently can not be treated by normal protection schemes, such as lighting arresters.

In this paper a model is developed for the H.V. windings of IPC transformer. This modeling technique is based on application of the multi-conductor transmission line theory (MTLT). The related software is developed in MATLAB domain, and by solving this model in frequency domain the oscillation frequencies are determined during application of fast transients which has short rise times. A typical IPC is modeled and simulated by EMTP, and the determined over voltages between adjacent coils and for inter-turns, at critical frequencies, are presented. It is shown that the related resonance frequencies located at 0.5 and 1.0 MHz frequencies.

Keywords: Transformer, IPC, Over voltage, Multi-Conductor Transmission Line

I. INTRODUCTION

Flexible AC Transmission Systems (FACTS) devices have been one of the most active and progressive fields of power systems as a tool for solving technical, economical and environmental problems. Power electronic improvements not only have expedited in the FACTS growth but also have proven new innovations in this field. Many different types of these devices have been introduced which in turn can control the power system transmission parameters.

IPC is one of the new technologies developed in recent years. This technology has been introduced in 80's for the first time [1, 2]. This device is actually an active and reactive power controller which can be located between two buses in series, and it has two parallel branches. It contains phase shifting transformers (PST), capacitors, reactors and some switches shown in Fig. 1 (Where; ψ_1, ψ_2 are the PST phase shifts).

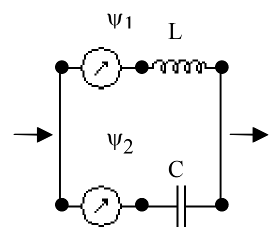

Fig. 1: Single line diagram of a typical IPC

IPC device has the following advantages [1- 4]:

1. Stabilizing of power flow in a tie-line between two power systems (within 10% deviation) for +/- of 25 degree of power angle (δ),
2. Active and reactive power control,
3. Filtering the distortions to prevent the related interactions,
4. Synchronic links without any changes in level of short circuit capacity, and
5. Operation without harmonics.

Using controlled capacitors and reactors, IPC can be used in dynamic and transient states rather than steady state [5]. Although IPC have special useful features in steady states, however their impact on power system during transient conditions should be studied for these applications. In this paper the response of the fast transient, by introduction of a multi-conductor transmission line model for transformer, have been studied, and related over voltages have been calculated and analyzed.

In the appendix, the advantages of IPC in comparison with other classic solution methods are presented [1].

Active power of IPC is less sensitive to the power angle (δ), while its reactive power is more sensitive to the δ which does not create any current harmonics. However, in a transmission line with series compensator and/or PST, the sensitivity of P to the δ, is more than the sensitivity of, Q to the δ [1, 3].

Based on IPC different applications; many different types have been employed [1, 3]. In this paper a specific type known as IPC120 has been studied. Fig. 2 shows its three phase diagram. Susceptances of B_1 and B_2 in receiving end (r) have been connected to the transformer primary circuit phases b, and c respectively (Yy6 is the transformer vector group with 180 degrees phase shift). The switches can carry even reverse

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power. Since the angle between these two phases is 120 degree, this IPC is called IPC120 [1, 3].

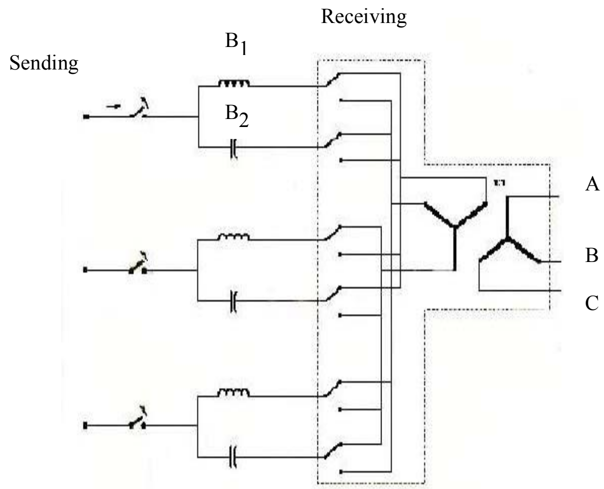


Fig. 2 : Schematic diagram of the typical IPC120

II. MODELING OF TRANSFORMER WINDING

The transformer H.V. winding is a complex combination of discs and each disc has many turns. For fast transient studies the nonlinear magnetic behavior of core can be neglected.

To model a transformer H.V. winding, two models can be suggested; Detailed model [6-8] and Multi-Conductor Transmission line (MTL) model [9-13].

In this paper the second model is studied. In this case two different modeling methods can be employed:

1. Each disc can be modeled with a multi-conductor transmission line. Actually, each loop can be modeled as an extended transmission line.
2. Each disc can be modeled in form of an extended single-conductor line.

For each of these two methods, the required parameters, such as: surge impedance and propagation coefficient, can be estimated [9, 10].

A. Model of a Multi-Conductor Transmission Line

In this case, each turn can be modeled with a transmission line and their combination is like a set of transmission lines which are geometrically in parallel, however electrically in series. In this case, a sinusoidal power supply with the amplitude of E_0 and angular frequency of ω has been connected to the input of this combination.

$(V(x))$ and $(I(x))$ present the voltages and the currents of multi-conductor transmission line. $[L]$ and $[C]$ are the inductance and capacitance matrices of the transmission line in the form of distributed coefficients [9-11].

$$\frac{d(V(x))}{dx} = -j\omega[L](I(x)) \quad (1)$$

$$\frac{d(I(x))}{dx} = -j\omega[C](V(x)) + j\omega(C_0)E_0 \quad (2)$$

The detailed definitions of distributed parameters are given in [11]. Solving the equations, then we have:

$$V_i(x) = k_i E_0 + A_i \exp(-\Gamma(\omega)x) + B_i \exp(\Gamma(\omega)x) \quad (3)$$

$$I_i(x) = (1/z_i)\{A_i \exp(-\Gamma(\omega)x) - B\exp(\Gamma(\omega)x)\} \quad (4)$$

The coefficients, A_i and B_i, are the value of surge voltages amplitude, at sending end and receiving end, which can be determined from boundary conditions. k_i Is the ratio of electrostatic induced voltage and Γ is the propagation coefficient.

v_s Velocity of electromagnetic wave in the insulator is:

$$v_s = \frac{c}{\sqrt{\varepsilon_r}} \quad (5)$$

$$[L] = \frac{[C]^{-1}}{v_s^{\,2}} \quad (6)$$

Where, c is the light speed in vacuum and ε_r is the insulator dielectric relative constant.

B. Model of a Single-Conductor Transmission Line

In this case, all the discs are modeled by a single-conductor transmission line and a set of similar equations derived as follows [9]:

$$V(x) = kE_0 + A\exp(-\Gamma(\omega)x) + B\exp(\Gamma(\omega)x) \quad (7)$$

$$I(x) = (1/z)\{A\exp(-\Gamma(\omega)x) - B\exp(\Gamma(\omega)x)\} \quad (8)$$

Surge impedances and coefficient of propagation can be estimated by comparison of these two models [9]:

$$z_i \cong \frac{1}{v_s\left(C_0 + C_1 + K\left(1 - \cos\left(\frac{\omega a}{v_s}\right)\right)\right)} \quad (9)$$

$$\Gamma = \frac{1}{v_s d}\sqrt{\frac{\omega}{2\sigma\mu}} + \frac{\omega \tan\delta}{2v_s} + \frac{j\omega}{v_s} \quad (10)$$

C. Model of Transformer Winding

An algorithm has been developed in [9] which can model the transformer windings. In this algorithm the discs of winding are modeled as a single-conductor transmission line and then the over voltages between discs are determined. With application of these results, any arbitrary disc can be selected and modeled by a multi-conductor transmission line, then the over voltages between turns are calculated.

III. SIMULATION

A. Frequency Domain Simulation

The method presented in the last section is applied to the IPC transformer windings. the technical specifications of this transformer are given in Table I. The transformer rating is 900 MVA, 500 kV with 1:1 ratio, Yy6 vector group, and its neutral is solidly grounded.

TABLE I
Technical specifications of IPC transformer windings

Disc date	Parameters related to surge propagation
Number of discs m=12	Dielectric constant of insulation $\varepsilon_r = 2.65$
Turn length $a^{(i)} = 6.83$ m	Surge velocity $\upsilon_s = 184 \ m/\mu_s$
Disc turns $N^{(i)} = 17, 17, 21, 21,$ $23, 23, 23, 23, 21, 21, 17, 17$	Dielectric loss factor $\tan \delta = 0.02$ Conductor conductance $\delta = 5 \times 10^7 \ s/m$
	$\mu = \mu_0 = 4\pi \times 10^{-7} \ H/m$ $d = 3.55 \ mm$
Disc capacitance	Distributed capacitance parameter of coil 1
Disc - Disc $C_m^{(i)} = 7500 \ p.F$	Inter-turn $k^{(i)} = 158$ pF/m
Disc - ground $C_g^{(i)} = 10 \ p.F$	Conductor static plate $C_0^{(1)} = 5.7675$pF/m $C_1^{(1)} = 64.59$ pF/m

It is assumed that a sinusoidal power supply with the amplitude of E_0 and angular frequency of ω is applied to the terminal of IPC. The transformer windings have been modeled as a set of transmission lines with frequency dependent parameters. The object of this paper is determination of IPC transformer resonance frequencies. As shown in Fig. 3 the characteristics impedance of each disc (Z_c) has been presented as a function of frequency. Considering the different location of each disc, the sensitivity of Z_c to the frequency are quite different for each disc.

Using this algorithm and the boundary conditions of multi- conductor transmission line theory, the absolute value of voltage between discs the respect to the input voltage can be determined for different type of transformer discs (Fig. 4). The inter-turn voltage of the first disc is presented in the Fig. 5. As it can be seen, there are two dominant resonances at 0.5 MHz and 1 MHz.

B. Time Domain Simulation

Time domain results of EMTP simulation for this IPC have shown in Fig. 6. A sinusoidal power supply with the frequency of 0.5 and 1 MHz has been applied to the IPC. The simulation results are presented in figures 7-10. As it can be seen the supply can excite the resonances between discs and turns.

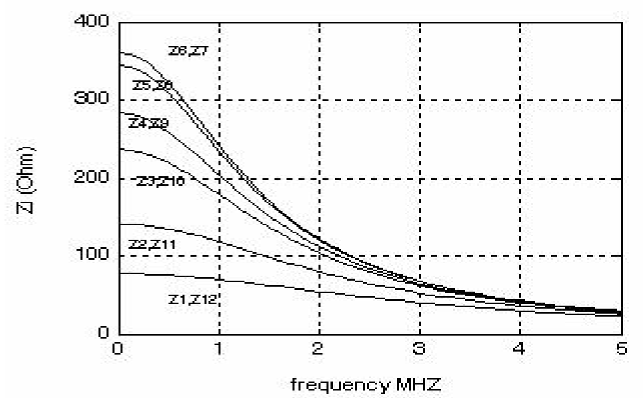
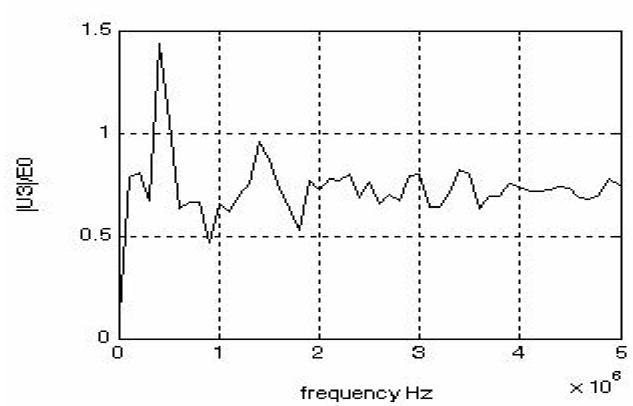


Fig. 3: Characteristic impedance of discs as a function of frequency (i=1,…,12)



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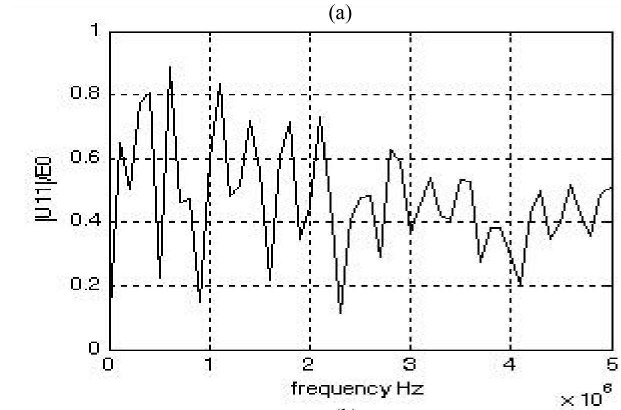

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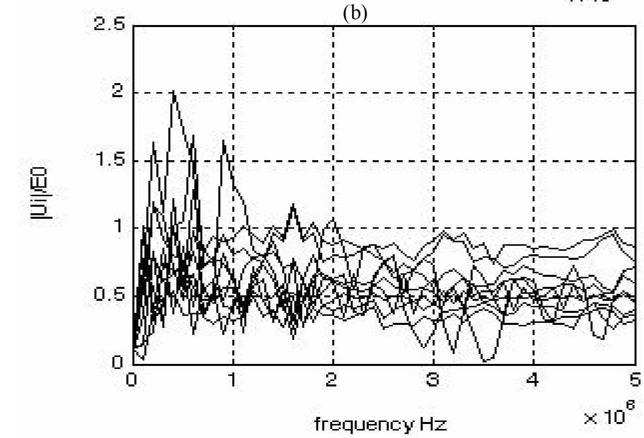


(c)

Fig. 4: Ratio of inter-discs voltage to its input voltage,
(a) Between Discs 3 and 4
(b) Between Discs 10 and 11
(c) Between every two other discs respectively

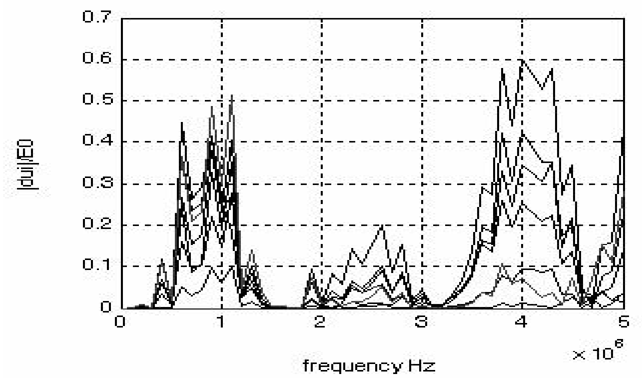


Fig. 5: Inter-turn voltages of the first disc

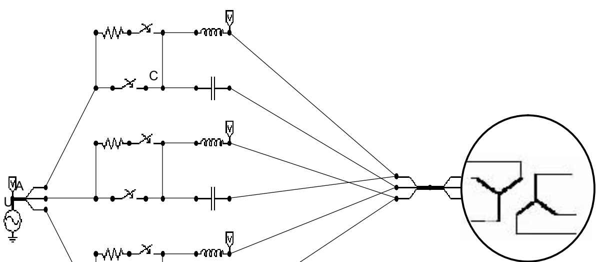
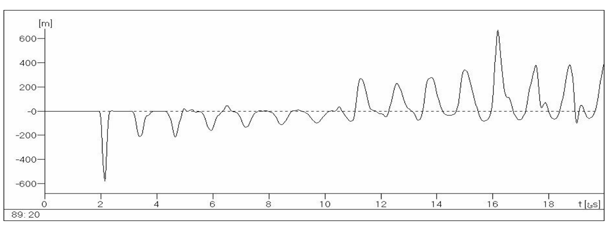


Fig. 6: In time domain simulated IPC with the transformer is modeled with MTLT and the sinusoidal power supply is shown (Inductances are 110 mH and capacitances are 0.12 F)



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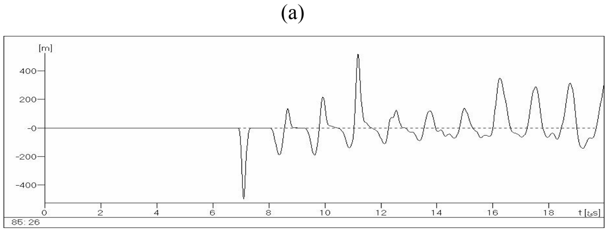

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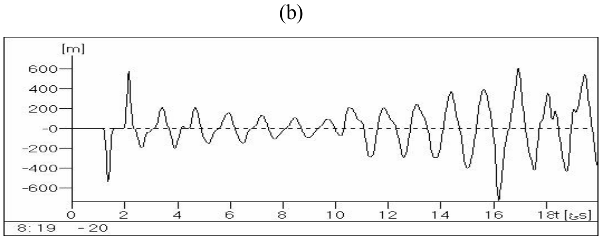

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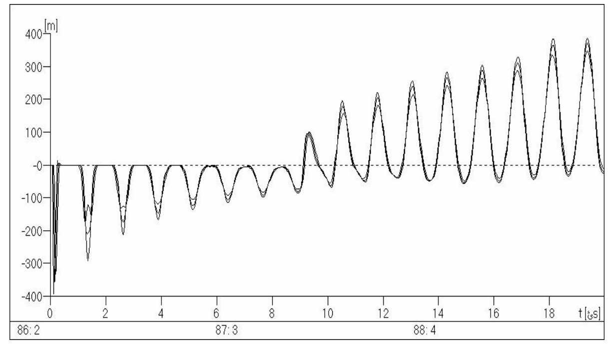
Fig. 7: 0.5MHz sinsuoidal supply,
(a) Voltage between discs No. 3 & No. 4,
(b) Voltage between discs No. 10 & No. 11 and
(c) Voltage of disc No. 3
x-axis is time (μsec) and y axis is voltage (mpu)



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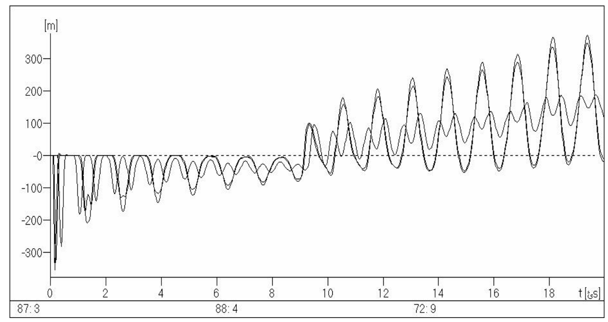
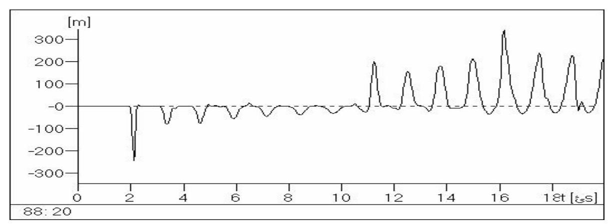


(b)

Fig. 8: 0.5 MHz sinusoidal supply,
(a) Voltage of turns No. 3, 4, 5
(b) Voltage of turns No. 10, 11, 12
x-axis is time (μsec) and y axis is voltage (mpu)



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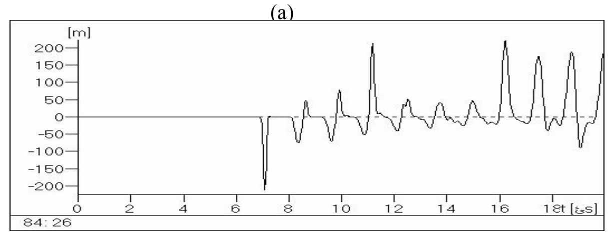

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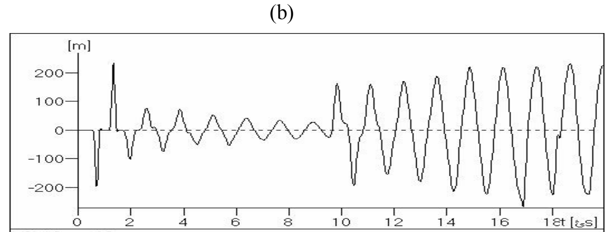
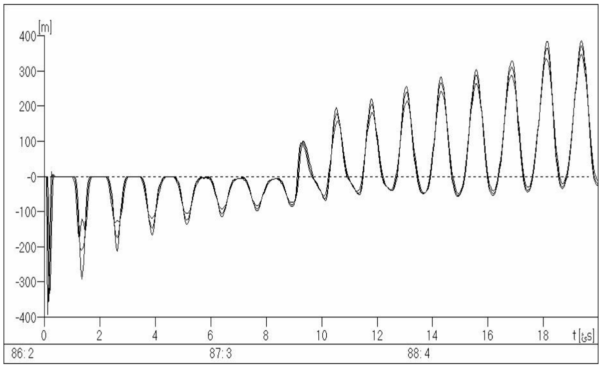


(c)

Fig. 9: 1MHz sinsuoidal supply,
(a) Voltage between discs No. 3 & No. 4,
(b) Voltage between discs No. 10 & No. 11 and
(c) Voltage of disc No. 3
x-axis is time (μsec) and y axis is voltage (mpu)



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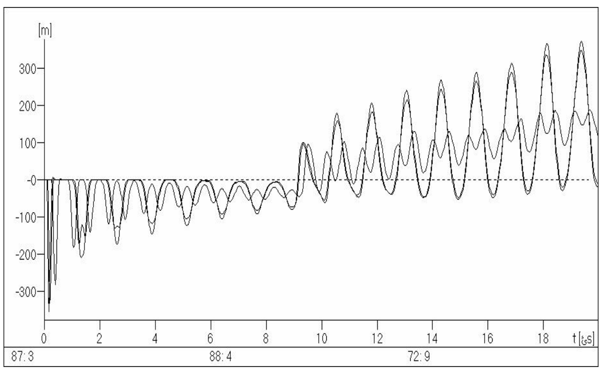

(b)

Fig. 10: 1 MHz sinusoidal supply,
(a) Voltage of turns No. 3, 4, 5
(b) Voltage of turns No. 10, 11, 12
x-axis is time (µsec) and y axis is voltage (mpu)

IV. CONCLUSION

This research discusses the transient behavior of IPC transformer. Two areas, of interest are covered in this study:

1- The sudden rise of voltage at the switching in start time, and
2- The transient characteristics of components.

Based on frequency and time domain simulation results, it is shown that the modeled IPC transformer have resonance frequencies at 0.5 and 1 MHz. This fact is important for the transformer designer. He must consider this fact in design stage. After design stage, one solution can be the application of closing resistance in circuit breakers to reduce and to limit the transient over voltages.

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VI. Appendix A

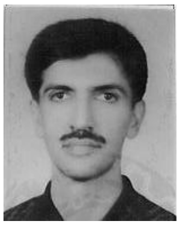
Table AI shows the advantages of IPC in comparison with other classic solutions for solving power system problems.

TABLE AI
The advantages of IPC

Application	Classic solution	Main advantage of IPC over classic solution
Asynchronous link	HVDC link	No generation of harmonic No reactive power consumption Robustness
Synchronous link	PST	Passive real power control Fault current limitation
Transformation capacity increase	System or transformer station redesign	Cost reduction in certain cases Maintenance of operating flexibility
Line power flow control	PST	Cost reduction Loss reduction

VII. BIOGRAPHIES

S.M.H. Hosseini was born in Tehran, Iran, on June 20, 1969. He received his B.Sc. degree in electrical power engineering from Ferdowsi university of Mashhad, Mashhad, Iran, in 1993. He received a M.Sc. degree in electrical power engineering from South-Tehran Azad University, Tehran, Iran, in 2000. From 2001 he is a Ph.D. student of Azad University, Tehran, Iran. From 1993 till yet he is the hydropower electrical expert of Iran Water and Power development resources Company (IWPCO). He joined the faculty of Azad University South-Tehran in 2000.



Mehdi Vakilian received his BSc in electrical engineering (1978) and MSc (1986) in electric power engineering from Sharif University of Technology in Tehran. PhD in electric power engineering from Rensselaer Polytechnic Institute, Troy, NY, USA in 1993.

He worked with Iran Generation and Transmission Company (Tavanir) as Manager of Transmission Network Operation Department (1981-1983), and as Director of Transmission & Distribution Education Planning Department of Iranian Ministry of Energy (1984-1985). From 1986 he joined the Faculty of Department of Electrical Engineering of Sharif University of Technology as Instructor. From 1993 he continued his work as Assistant Professor in electric power engineering; from 1997 to 2001 he was also Director of Electric Power Group. From 2001 to 2003 he was Associate Professor and also Chairman of the Department. His research interest is transient modeling of power system equipments, optimum design of high voltage equipments insulation, and insulation monitoring.

During September 2003 to September 2004 he was on leave of study at School of Electrical Engineering & Tel. of University of New South Wales, Sydney. Where he concentrated his research on study of PD signals propagation in XLPE cables.

At present he is also director of restructuring committee of Electrical Engineering education in Sharif University.

G.B. Gharehpetian was born in Tehran, in 1962. He received his BS and MS degrees in electrical engineering in 1987 and 1989 from Tabriz University, Tabriz, Iran and Amirkabir University of Technology (AUT), Tehran, Iran, respectively, graduating with First Class Honors. In 1989 he joined the Electrical Engineering Department of AUT as a lecturer. He received the Ph.D. degree in electrical engineering from Tehran University, Tehran, Iran, in 1996. As a Ph.D. student he has received scholarship from DAAD (German Academic Exchange Service) from 1993 to 1996 and he was with High Voltage Institute of RWTH Aachen, Aachen, Germany. He held the position of Assistant Professor in AUT from 1997 to 2003, and has been Associate Professor since 2004.

Dr. Gharehpetian is a Senior Member of Iranian Association of Electrical and Electronics Engineers (IAEEE), member of IEEE and member of central board of IAEEE. Since 2004 he is the Editor-in-Chief of the Journal of IAEEE. The power engineering group of AUT has been selected as a Center of Excellence on Power Systems in Iran since 2001. He is a member of this center and since 2004 the Research Deputy of this center.

He is the author of more than 120 journal and conference papers. His teaching and research interest include power system and transformers transients, FACTS devices and HVDC transmission.