Variable-Speed Prime Mover Driving Three-Phase Self-Excited Induction Generator with Static VAR Compensator Voltage Regulation–Part II : Simulation and Experimental Results–

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Abstract - This paper presents the digital computer performance evaluations of the three-phase self-excited induction generator (SEIG) driven by the variable speed prime mover such as the wind turbine using the nodal admittance approach steady-state frequency domain analysis with the experimental results. The three-phase SEIG setup is implemented for small-scale rural renewable energy utilizations. The experimental performance results give a good agreement with those ones obtained from the digital computer simulation. Furthermore, a feedback closed-loop voltage regulation of the three-phase SEIG as a power conditioner which is driven by a variable speed prime mover employing the static VAR compensator (SVC) circuit composed of the thyristor phase controlled reactor (TCR) and the thyristor switched capacitor(TSC) is designed and considered herein for the wind-turbine driven the power conditioner. To validate the effectiveness of the SVC-based voltage regulator of the terminal voltage of the three-phase SEIG, an inductive load parameter disturbances in stand-alone are applied and characterized in this paper. In the stand-alone power utilization system, the terminal voltage response and thyristor triggering angle response of the TCR are plotted graphically. The simulation and the experimental results prove the effectiveness and validity of the proposed SVC which is controlled by the PI controller in terms of fast response and high performances of the three-phase SEIG driven directly by the rural renewable energy utilization like a variable-speed prime mover.

Keywords: three-phase self-excited induction generator, static VAR compensator, thyristor phased controlled reactor, thyristor switched capacitor, feedback terminal voltage regulation scheme, power conditioner, rural renewable energy and variable-speed prime mover

1. Introduction

The wind Power generation has become increasingly more and more popular in the past few years especially after the 1970s during the energy crisis, the use of the wind power for electrical generation has been started in a major way. Many applications are related to large-scale, utility-size wind parks where thousands of wind turbines are interconnected to generate large-scale electricity in the rural residential applications. In some other parts of the world, wind turbines are installed on a smaller scale. Most wind turbines are equipped with line-connected induction generators. The squirrel cage induction generators are very attractive as wind turbine generators due to their low cost, ruggedness, high reliability and the need for little or no maintenance. At constant frequency, the induction generator operates in a small range of speeds. Therefore , it operates with a small range of slips with respect to synchronous speed. Compared to a synchronous generator, an induction generator provides lower stiffness, thus alleviating the mechanical stress. On the other hand, the stand–alone generating systems using wind turbines or diesel engines have been widely used for emergency supply in the plants or isolated islands and so on. However, in these cases, the synchronous generator is usually used. If the output frequency of the three-phase self-excited induction generator SEIG is to be kept constant, there is the need to control the speed of the diesel engine using a high performance governor. Even then, the output frequency changes in case of a sudden load change. In the case of an utility connected generator, the output voltage and frequency have been already determined by the utility, but in case of a stand-alone generating system, the generator must determine and establish the output voltage and frequency by itself. Possible and effective applications for the power conditioning system in variable-speed generation are currently under investigation. The generated output voltage can be directly connected to load facilities and equipment are non-sensitive to the frequency which includes a heater, battery charger,

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double converter etc. or can be connected through a double converter to get a fixed-frequency AC output.

In this paper, we propose a new stand-alone power generating system. In our proposal, the absolute constant output voltage can be obtained even though rotor speed changes with the load disturbances.

This paper presents the experimental performance results and the computer simulation results to verify the theoretical performance analysis utilizing the nodal admittance approach for the three SEIG driven by variable-speed prime mover in a certain isolated stand-alone operation. The experimental performance results are presented to support the frequency domain analysis. In addition, a closed loop PI compensator for the terminal voltage regulation of the three-phase SEIG driven directly by variable-speed prime mover is established using the SVC composed of thyristor phased controlled reactor TCR and thyristor switched capacitor TSC.

The performances of the three-phase SEIG are evaluated and discussed as a stand-alone power conditioner on the basis of the simulation and the experimental results. The effectiveness of the power conditioner treated here is proved as rural renewable energy power utilizations.

2. System Description

The proposed stand-alone power conditioner voltage regulation scheme is depicted in Fig 1. In this configuration, a load is connected to the stator winding side of the three-phase squirrel cage rotor self-excited induction generators and the static VAR compensator composed of the fixed excitation capacitor bank; FC, the thyristor phased controlled reactor TCR in parallel with the thyristor switched capacitor TSC which is controlled by a closed-loop feedback PI controller. The stator voltage is controlled to be constant through the control of the reactive power required for the power system from the static VAR compensator. The three-phase 4 poles, 220 V, 2 kW, Y connected squirrel cage rotor induction generator supplies to the resistive or inductive load. The induction generator excited by the fixed capacitor bank and SVC composed of the TSC and the TCR which consists of phase control anti-parallel thyristors connected in series with an inductor. The thyristors triggering circuits and the PI controller circuits are designed for regulating the terminal generated voltage of the three-phase self-excited induction generator[1-13]. Table 1 includes the design specifications and circuit parameters of the voltage regulation system description for the three-phase SEIG with SVC controlled by the PI controller.

Table 1 Design Specifications and Circuit Parameters

Items	Machine Rating and Machine Parameters	
Three-Phase Star Connected Induction Machine with Squirrel Cage Rotor	Rated Voltage	220 V
	Rated Power	2 kW
	Number of Poles	4
	Rated Frequency	50 Hz
	Rotor Type	Squirrel Cage
	Induction Machine Parameters at 50 Hz	
	R_l=0.517 ohm	X_l=1.0063 ohm
	R_2=0.517 ohm	X_1=1.0063 ohm
SVC composed of FC, TCR &TSC	X_{TCR} at 50 Hz;L_{TCR}	56 ohm, 0.178 H
	X_C at 50 Hz; C	13 ohm,243.5 μF
	X_{TSC} at 50 Hz; C_{TSC}	31.8 ohm,100 μF
PI Controller	K_P	0.01
	K_I	0.125
VSPM (dc Motor)	t_o	120.08
	υ_o	132.6
Per-Phase Passive Load Components	R_L	35-200 ohm
	X_L at 50 Hz	25-140 ohm

3. Simulation and Experimental Results and Discussions

The steady-state analysis of the three-phase SEIG as a stand-alone system is based on its equivalent circuit. The nodal admittance approach is applied to determine its performance characteristics of the three-phase SEIG driven by variable-speed prime movers; the wind turbine or the micro gas turbine. A prototype of the three-phase SEIG is built and tested actually. Fig.2 represents the variation of the terminal output voltage and the output power when the three-phase SEIG is excited by three different capacitor capacitances(C=194.2 μF, 243.5 μF and 294.3 μF per phase) and supplying to a resistive load. Fig.3 depicts the terminal voltage variations against the prime mover shaft speed, in this case, the dc motor, when the three-phase SEIG is loaded by a resistive load, Fig.2 and Fig.3 show that the terminal voltage decreases as increasing the output power, and the prime mover speed decreases in accordance with the torque-speed characteristics of the variable speed prime mover. For inductive loading condition at 0.82 lagging power factor and various excitation capacitor capacitances, Fig.4 illustrates the induction generator terminal output voltage variations with the output power calculated from the digital simulation and experimental results. Fig.5 represents the terminal output voltage vs. the prime mover shaft speed characteristics. The terminal output voltage decreases with the inductive load and the maximum output power is found to be less than when the three-phase SEIG loaded by a resistive load.

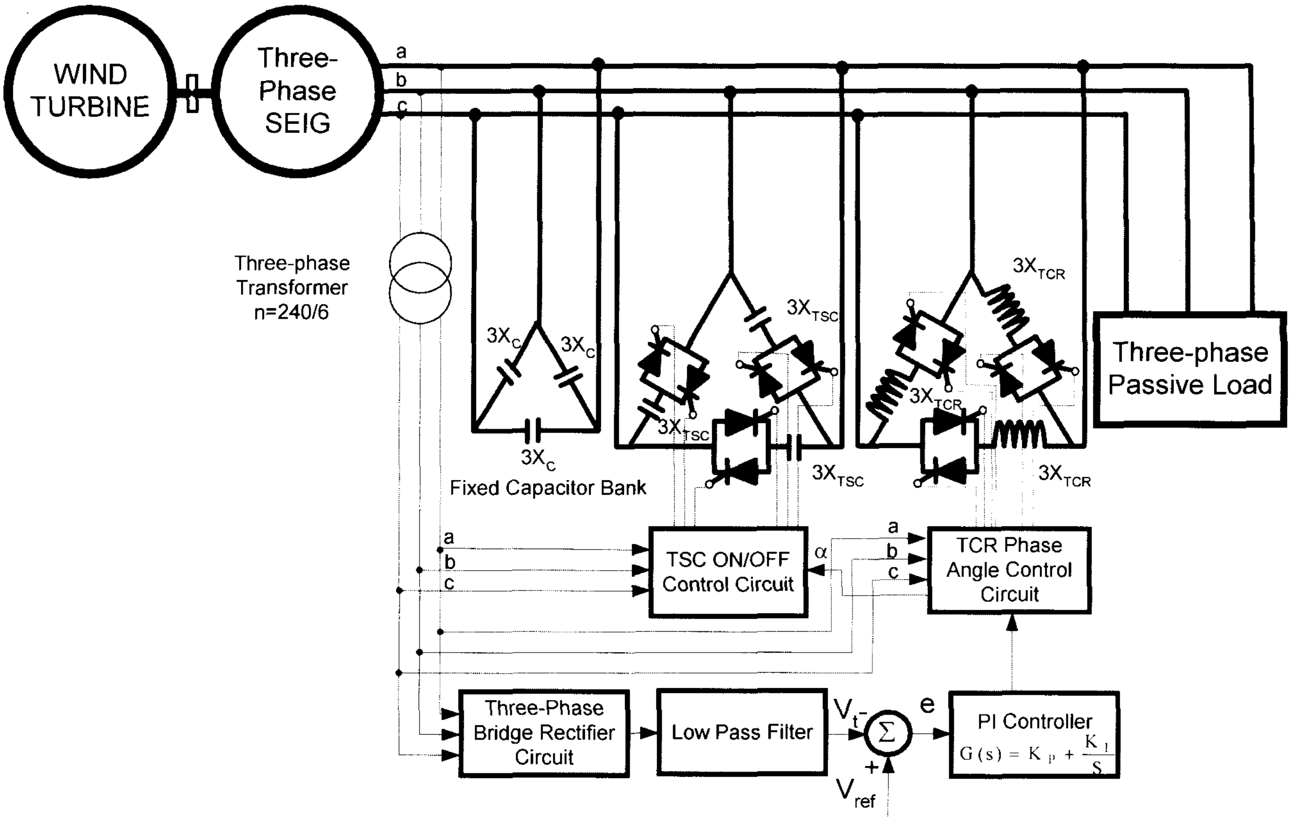


Fig.1 A Schematic diagram of the three-phase SEIG driven by variable speed prime mover with SVC(TCR-TSC/FC types)controlled by PI controller

Due to the prime mover speeds and the load fluctuating, the terminal output voltage of the three-phase SEIG are changed and unregulated. The static VAR voltage regulation compensator connected to the three-phase SEIG terminals is used to regulate its terminal output voltage. The schematic diagram of the three-phase SEIG driven directly by the variable speed prime mover with SVC composed of the TCR and the TSC including the PI controller is shown in Fig.1. The terminal output voltage of the three-phase SEIG changes in accordance with the load variations which also affect on the prime mover speed. The static VAR compensator composed of the TCR and the TSC controlled by the PI controller voltage regulator to adjust the terminal voltage, shown in Fig.1. The computer simulation results and the experimental three-phase SEIG responses due to the inductive load variations under conditions of increasing the values of the load components R_L and X_L and then decreasing the values of the load components R_L and X_L is defined in terms of the terminal voltage and thyristor triggering delay angle responses are illustrated respectively, in Fig.6, Fig.7, Fig.8 and Fig.9. From the above figures, the generated terminal voltage of the three-phase SEIG raises on the sudden increasing of the load parameters values R_L and X_L. The feedback closed-loop PI controller adjusts the controlled virtual reactive susceptance of the TCR by increasing its conduction angle σ, i.e. decreasing the triggering angle α of the TCR thyristor. The TCR virtual reactive susceptance value will be increased until the generated terminal voltage of the Three-phase SEIG is regulated to the desired value or the reference value, 220 Volt. Upon sudden application or decreasing the load components R_L and X_L values, the generated terminal voltage of the three-phase SEIG effective value will be decreased. The triggering angle of the TCR thyristor increases to decrease the controlled reactive susceptance of the TCR by the feedback closed loop PI controller output signal error voltage until the error voltage equals to zero. When a large load is connected to the three-phase SEIG terminals the firing angle of the TCR thyristor increased until it is equal to π, i.e. the TCR thyristor is off. The generated terminal voltage of the three-phase SEIG is still less than the desired value 220 Volt. An additional excitation capacitor capacitance required, The TSC switched on and connected to the three-phase SEIG terminals in parallel with the TCR , the generated terminal voltage of the three-phase SEIG will raise over the desired value 220 Volt. The PI controller adjusts the controlled virtual susceptance of the TCR until the error voltage equals to zero.

With inductive loads, the terminal SVC composed of the fixed excitation capacitor bank; FC in parallel with the

TCR and the TSC must be provide the reactive power of inductive load and the three-phase SEIG.

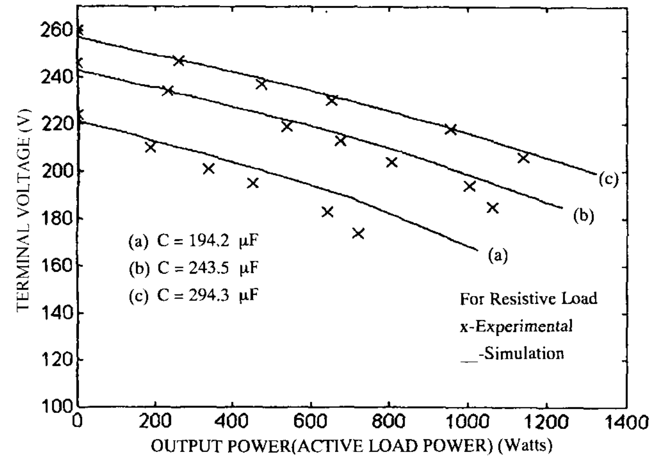


Fig. 2 Terminal voltage variation of the three-phase SEIG loaded by a resistive load at different excitation capacitances

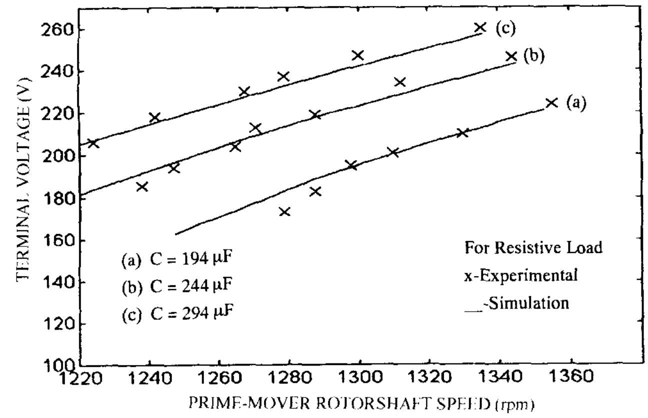


Fig. 3 Terminal voltage variation of the three-phase SEIG loaded by a resistive load against its rotor speed at different excitation capacitances

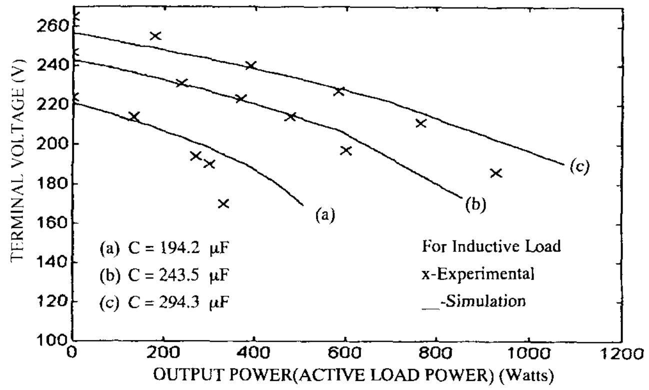


Fig. 4 Terminal voltage variation of the three-phase SEIG loaded by a0.82 lagging power factor load at different excitation capacitances

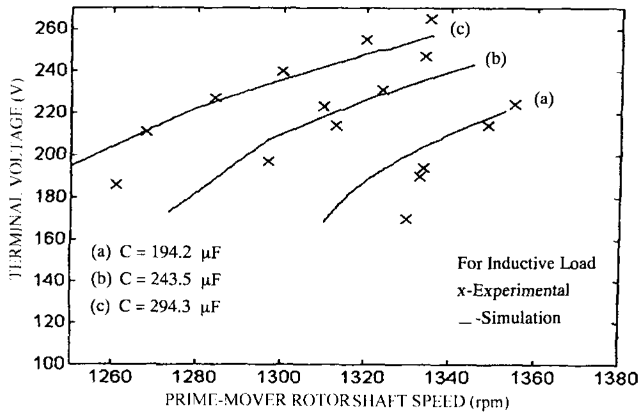


Fig. 5 Terminal voltage variation of the three-phase SEIG loaded by a0.82 lagging power factor load against its rotor speed at different excitation capacitances

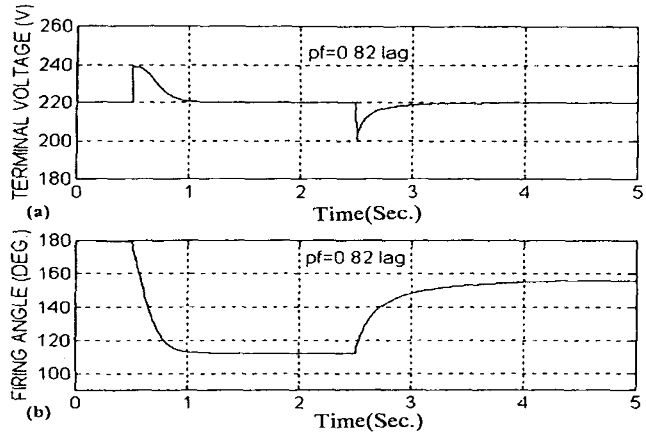


Fig. 6 Three-phase SEIG Digital response using SVC composed of FC and TCR and 0.82 lagging power factor load due to load variations

(a)Terminal Voltage response (b)TCR thyristor firing angle response

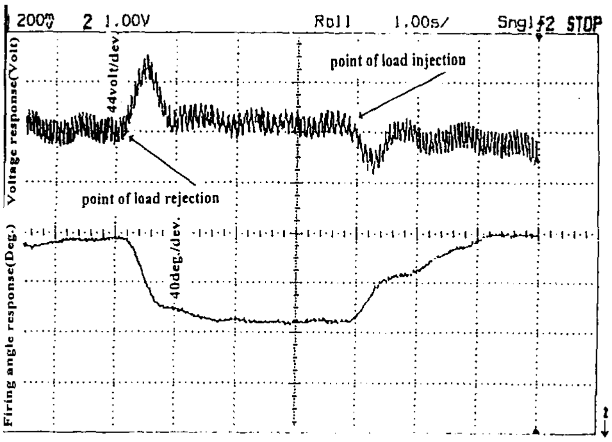


Fig. 7 Three-phase SEIG Experimental terminal voltage and thyristor firing angle responses using SVC composed of FC and TCR and 0.82 lagging power factor load due to load variations

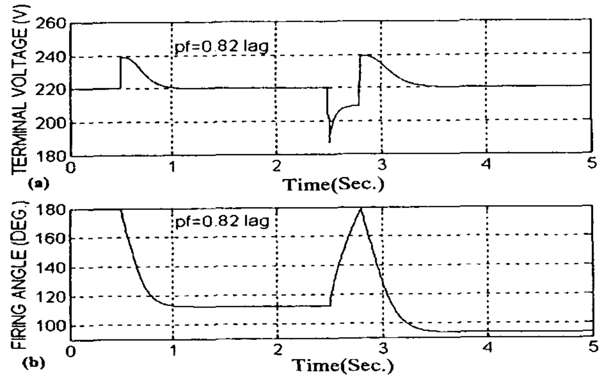


Fig. 8 Three-phase SEIG Digital response using SVC composed of FC , TSC and TCR and 0.82 lagging power factor load due to load variations (a)Terminal Voltage response (b) TCR thyristor firing angle response

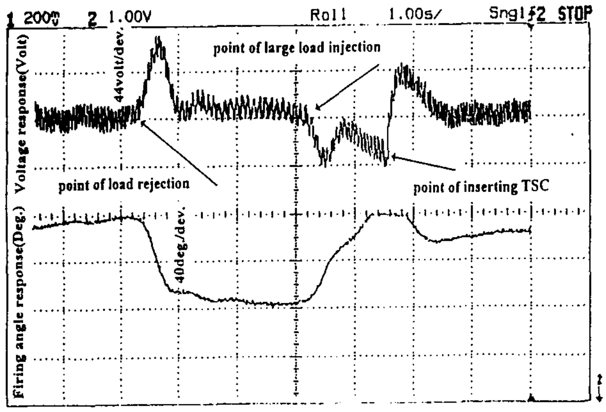


Fig. 9 Three-phase SEIG Experimental terminal voltage and thyristor firing angle responses using SVC composed of FC , TSC and TCR and 0.82 lagging power factor load due to load variations

The above results prove a good agreement between the characteristics of the three-phase SEIG obtained from the computer simulation and experimental results carried out for the voltage regulation of the three-phase SEIG. The coincidence of the experimentally obtained results and theoretical simulation results proves the validity of the derived models and the modification of the available models. The approach for the variable speed prime mover cases is verified to be correct and valid for the future

4. Conclusions

The present paper has evaluated by using an algorithm for steady-state frequency domain analysis of the three-phase SEIG stand-alone system, which is driven by variable-speed prime-mover; the steady-state performances of the three-phase SEIG have obtained in terms of variations of the terminal output voltage in accordance with output power and prime-mover speed. In addition, this paper has presented a static VAR controller for voltage regulation of the three-phase SEIG for the external disturbances such as the load applied to build and test the static VAR compensator system. It has noted that the good and the stable three-phase SEIG responses in terms of the terminal voltage response validated the effectiveness of the static VAR compensator system. The experimental characteristic curves of the induction generator performance have showed a good agreement with those obtained from the digital simulation results. A three-phase SEIG prototype system has established for the power conditioner.

References

[1] Michael Liwschitz-Garik and Clyde C.Whipple, "Alternating current Machines", D.Van Nostrand company, NJ, 1961.

[2] A.F.Puchstein, T.C.Lioyd and A.G.Conard, "Alternating current Machines", John Wiley, 1954.

[3] M.Konstenko and L.Piotravsky, "Electrical Machines", Mir Publishers, Moscow, 1969.

[4] Bhim Singh, "Induction Generator- a Prospective", Electric Machines and Power Systems, Vol.23, pp.163-177, 1995.

[5] M.Ermis, H.B.Erton, M.Demirekler, B.M.Saribatir, Y.Uctvg, M.E.Sezer and I.Cadirici, "Various Induction Generator Schemes for Wind-Electricity Generation", Electric Power Systems Research, Vol.23, pp.71-83, 1992

[6] A.A.Shaltout and M.A.Adel-Halim, "Solid State Control of Wind-Driven Self-Excited Induction Generator", Electric Machines and Power Systems, Vol.23, pp.571-582, 1995

[7] T.F.Chan, "Analysis of Self-Excited Induction Generator Using an Iterative Method", IEEE Trans. On Energy Conversion, Vol.EC-10, No.3 pp.502-507, September, 1985.

[8] S.P.Singh, M.P.Jain and Bhim Singh, "A New Technique for Analysis of Self-Excited Induction Generator", Electric Machine and Power Systems, Vol.23, pp647-656, 1995.

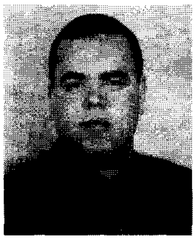
[9] T.F.Chan, "Capacitance Requirements of Self-Excited Induction Generators", IEEE Trans. On Energy Conversion, Vol.8, No.2 pp.304-311, June, 1993.

[10] S.Rajakarvna and R.Bonert, "A Technique for The Steady state Analysis of Self-Excited Induction Generator with variable speed", IEEE Trans. On Energy Conversion, Vol.10, No.1, pp.10-16, March, 1995.

[11] W. Koczara, et al: "Variable Speed Three-Phase Power Generation Set", EPE-2001, 2001.

[12] A. Koyanagi et al: "Maximum Power Point Tracking of Wind Turbine Generator Using a Flywheel", Proceedings of the 2001 Japan Industry Application society Conference, Vol.1, pp395-398, 2001.

[13] IEEE Special Stability Controls Working Group Report, "Static VAR Compensator Models for Power Flow and Dynamic Performance Simulation", IEEE Transactions on Power Systems, Vol.9, No.1 February, 1994



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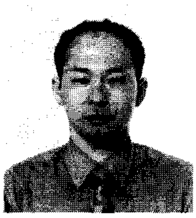

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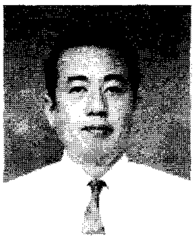

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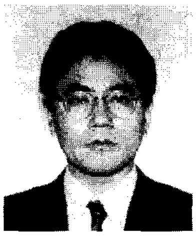

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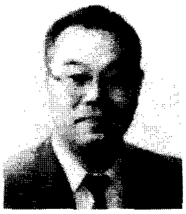

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