Single-Phase Self-Excited Induction Generator with Static VAR Compensator Voltage Regulation for Simple and Low Cost Stand-Alone Renewable Energy Utilizations
Part Ⅱ : Simulation and Experimental Results

Tarek Ahmed*, Osamu Noro, Koji Soshin*, Shinji Sato*, Eiji Hiraki* and Mutsuo Nakaoka***

Abstract - In this paper, the power conditioner composed of the stand-alone single-phase squirrel cage rotor type self-excited induction generator (SEIG) driven by prime movers such as a wind turbine and a micro gas turbine (MGT) is presented by using the steady-state circuit analysis based on the the two nodal admittance approaches using the per-unit frequency in addition to a new state variable defined by the per-unit slip frequency along with its performance evaluations for the stand-alone energy utilizations. The stande-alone single-phase SEIG operating performances in unregulated voltage control loop are then evaluated on line under the conditions of the speed change transients of the prime mover and the stand-alone electrical passive load power variations with the simple theoretical analysis and the efficient computation processing procedures described in the part I of this paper. In addition, a feasuible PI controlled feedback closed-loop voltage regulation scheme of the stande-alone single-phase SEIG is designed on the basis of the static VAR compensator (SVC) and discussed in experiment for the promising stand-alone power conditioner. The experimental operating performance results are illustrated and give good agreements with the simulation ones. The simulation and experimental results of the stand-alone single-phase SEIG with the simple SVC controller for its stabilized voltage regulation prove the practical effectiveness of the additional SVC control loop scheme including the PI controller with fast response characteristics and steady-sate performance improvements.

Keywords: single-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 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 rotor type 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. In the case of a utility connected generator, the output voltage and frequency have been already determined by the utility, but in case of a stand-alone generating plant, 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, super capacitor energy storage etc. for stand-alone applications or can be connected through a double converter to get a fixed-frequency AC output.

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

This paper presents the experimental performance results and the computer simulation results of the comparative steady-state operating performance analysis algorithms of the stand-alone single-phase self-excited induction generator (SEIG) on the basis of the two nodal admittance ap-

---

* Dept. of Electrical and Electronic Engineering, Yamaguchi University, Japan. (tarek@pe-news1.eee.yamaguchi-u.ac.jp)
** Kawasaki Heavy Industry, Kobe, Japan

Received February 6, 2003 ; Accepted March 8, 2003.

proaches using the per-unit frequency in addition to a new state variable defined by the per-unit slip frequency to verify the theoretical performance analysis in a certain isolated stand-alone operation with the simple mathematical computation effort[1-12]. 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 single-phase SEIG driven directly by constant-speed prime mover is established using the SVC composed of the fixed excitation capacitor FC in parallel with thyristor phase controlled reactor TCR and thyristor switched capacitor TSC. The performances of the single-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. Experimental Results and Discussions in Open Loop Voltage Regulation Implementation

Assume that a single-phase SEIG with a passive electrical load for the stand-alone renewable energy utilization is operating under no-load condition. In this case, the excitation capacitor capacitance 294 μF is used. The output frequency of the single-phase SEIG vs. the prime mover rotor shaft speed is illustrated in Fig.1 by using the conventional per-unit frequency f and the proposed per-unit slip frequency s_f state variables and they are also verified by the feasible experimental set-up in the laboratory of the single-phase SEIG. Furthermore, the no-load generated terminal voltage of the single-phase SEIG against the prime mover rotor speed characteristics at the same mentioned above the excitation capacitor capacitance is illustrated in Fig.2. From the above figures, it is noted that the proposed per-unit slip frequency based nodal circuit analysis approach it gives good results as compared with the per unit frequency-based nodal circuit analysis method. It has some merits over the per unit frequency-based nodal circuit analysis method for simplicity of the calculation and less computer requirement memory. For resistive and inductive with 0.9 lagging power factor load conditions, and the excitation capacitor capacitance designed for 294 μF is connected to the single-phase SEIG output terminal ports, the electrical output and the generated terminal voltage of the mechanical variations with the rotor shaft speed are plotted and shown in Fig.3, Fig.4, Fig.5 and Fig.6, respectively. Moreover, Fig.7 and Fig.8 demonstrate the generated terminal voltage of the single-phase SEIG vs. the load current at excitation capacitor capacitance designed for 194.2 μF, and the rotor shaft speed N=1400 rpm, for both a resistive load and an inductive load with 0.9 lagging power factor, respectively. The experimental and the computer simulation curves prove good agreements between the single-phase SEIG operating performances using the proposed per-unit slip frequency s_f for the steady-state analysis and the experimental results in addition to using the per-unit frequency of steady-state operating analysis.

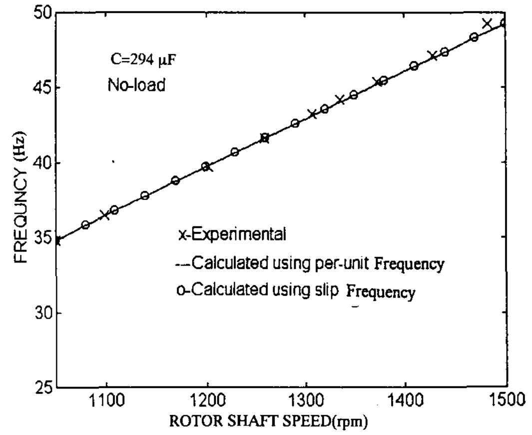


Fig. 1 Single-phase SEIG output frequency vs. rotor shaft speed at no load.

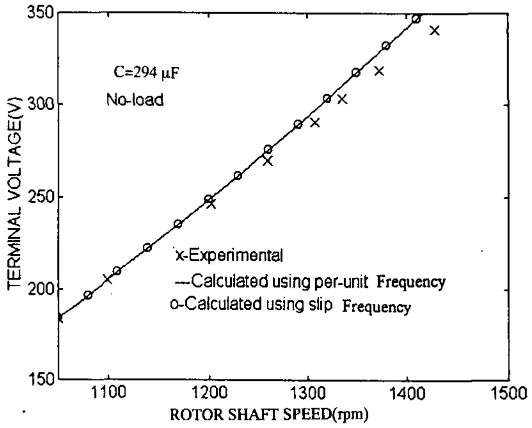


Fig. 2 Terminal voltage variations of single-phase SEIG against rotor shaft speed at no load.

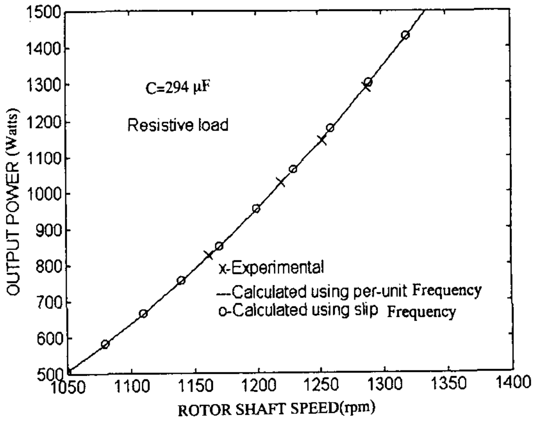


Fig. 3 Single-phase SEIG output power against rotor shaft speed for a resistive load

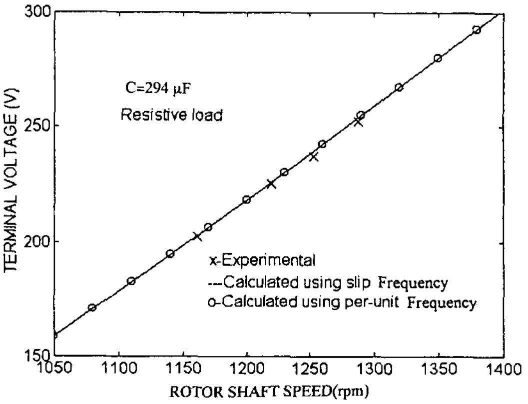


Fig. 4 Terminal voltage variations of the single-phase SEIG against prime mover rotor speed

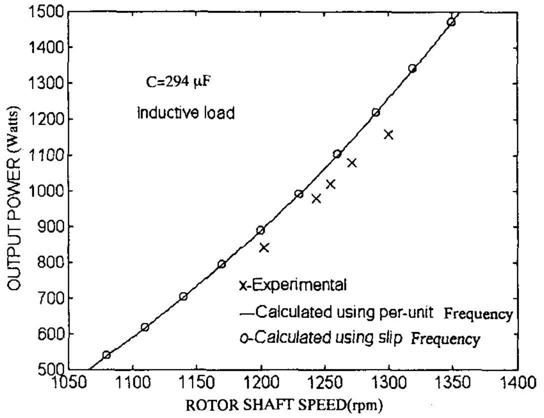


Fig. 5 Single-phase SEIG terminal voltage variation vs. the load current for a resistive load

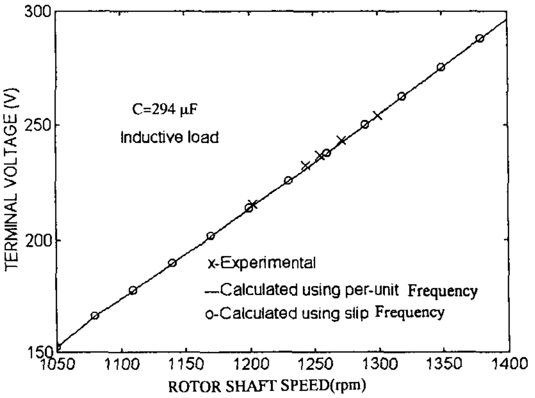


Fig. 6 Terminal voltage variation of single-phase SEIG against the prime mover speed

3. SVC-based Voltage Regulation Scheme of Single-Phase SEIG in Parallel with Passive Load

The proposed stand-alone power conditioner voltage regulation scheme is depicted in Fig 9. In this configuration, a load is connected to the stator winding side of the single-phase squirrel cage rotor type self-excited induction generators and the static VAR compensator composed of the fixed excitation capacitor; FC, the thyristor phase 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 single-phase 4 poles, 240 V, 2 kW, Y connected squirrel cage rotor type induction generator supplies to the resistive or inductive load. The induction generator excited by SVC composed the fixed capacitor FC in parallel with the TSC and the TCR composed of single-phase phase control anti-parallel thyristors connected in series with an inductor. The thyristors triggering circuits and the PI controller circuits are designed and shown in Fig.10 and Fig.11, respectively, for regulating the terminal generated voltage of the single-phase self-excited induction generator[1-12]. Table 1 includes the design specifications and circuit parameters of the voltage regulation system description for the single-phase SEIG with SVC adjusted by the PI controller in the feedback loop.

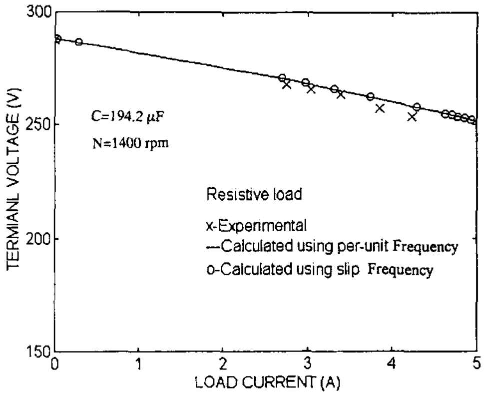


Fig. 7 Terminal voltage variation of single -phase SEIG against the load current

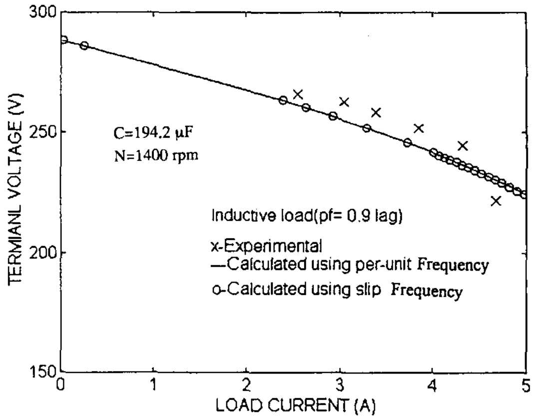


Fig. 8 Terminal voltage variation of single -phase SEIG against the load current

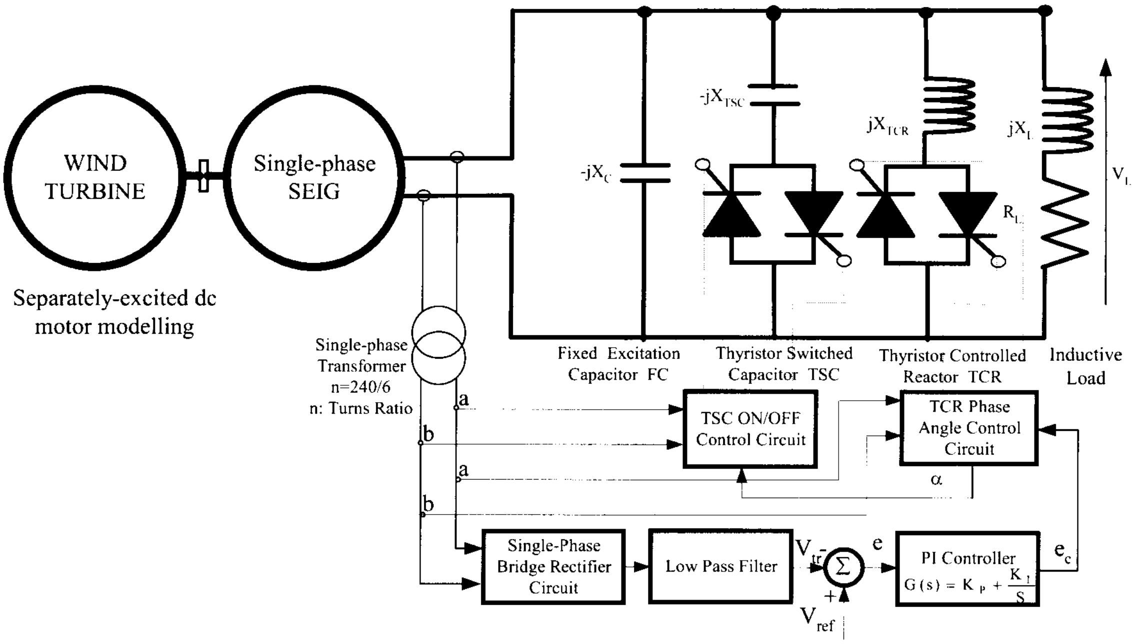


Fig. 9 A schematic system configuration of single-phase SEIG wind turbine regulated speed with SVC voltage regulation feedback closed loop scheme

Table 1 Design Specifications and Circuit arameters

Items	Machine Rating and Machine Parameters	
Single-Phase Star Connected Induction Machine with Squirrel Cage Rotor	Rated Voltage	240 V
	Rated Power	2 kW
	Number of Poles	4
	Rated Frequency	50 Hz
	Rotor Type	Squirrel Cage
	Induction Machine Parameters at 50 Hz	
	R_1=1.40 ohm	X_1=2.10 ohm
	R_2=0.59 ohm	X_2=1.05 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	0.38
	K_I	12.5
Per-Phase Passive Load Components	R_L	35-200 ohm
	X_L at 50 Hz	25-140 ohm

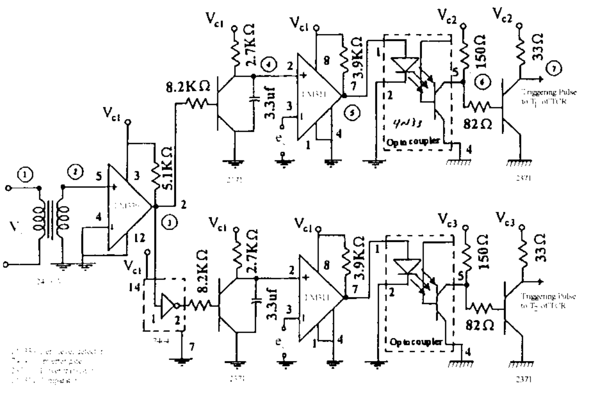


Fig.10 Designed thyristors triggering circuit

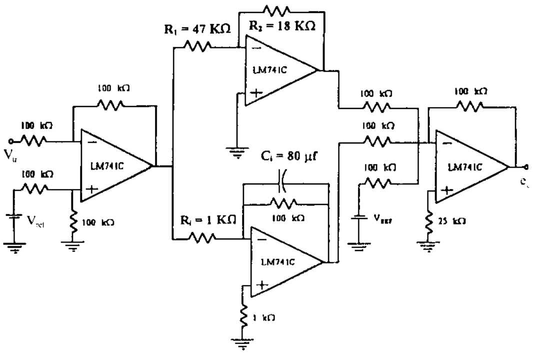
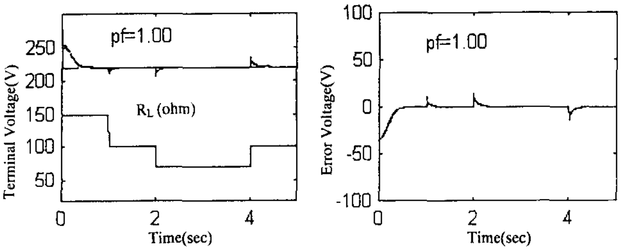


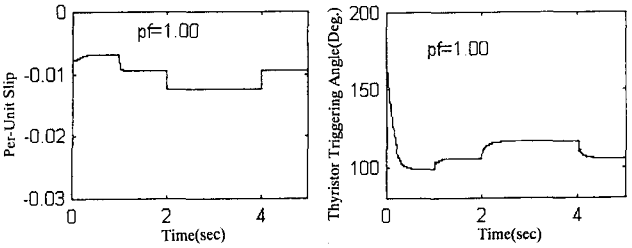
Fig. 11 Designed PI controller circuit

4. Experimental and Simulation Results in Closed Loop Voltage Regulation Implementation

Fig. 9 illustrates the terminal output voltage regulation feedback closed-loop with the single-phase SVC including the single-phase SEIG block diagram. To validate the practical effectiveness of the single-phase SVC for regulating the generated terminal voltage of the single-phase SEIG, the single-phase SEIG loaded by the electrical resistive load for stand-alone applications. Next, the resistive load is changed for observing the action of the SVC to regulate the terminal voltage of the single-phase SEIG. Fig.12(a) illustrates the terminal voltage response of the single-phase SEIG when the resistive load changes. The terminal voltage error during the closed loop voltage regulation response period is shown in Fig.12(b). While Fig.12(c) shows the per unit slip response and the thyristor triggering delayed angle α response of the TCR is illustrated in Fig.12(d). Moreover, when an inductive passive load with 0.9lag. power factor is loaded for the single-phase SEIG, the terminal voltage ,error voltage, per-unit slip and the thyristor triggering delayed angle α responses in the TCR are shown in Fig.13(a), Fig.13(b), Fig.13(c) and Fig.13(d), respectively. Furthermore, The SVC composed of the TCR and the FC could regulate the generated terminal voltage under the conditions of the single-phase SEIG loading conditions above. However, when its loading conditions increase for loading impedance decreases, the SVC employed here can not stabilize and reinforce the generated terminal voltage of the single-phase SEIG so as to follow up the reference terminal voltage. To increase the allowable application range of the single-phase SVC, an additional thyristor switched capacitor; TSC is connected in parallel with the TCR and the FC. For the terminal generated voltage response, its error response in feedback control system, per unit slip response and the thyristor triggering delayed angle response of TCR in the closed feedback loop voltage regulation of the single-phase SEIG with SVC composed of TCR in parallel with FC and then TSC in parallel with TCR and FC are shown in Fig.14(a), Fig.14(b), Fig.14(c) and Fig.14(d) and Fig.15(a), Fig.15(b), Fig.15(c) and Fig.15(d), respectively. The measured single-phase SEIG voltage regulation response and thyristor trigging delayed angle response due to the inductive passive load variations under the conditions of increasing the values of the load components of R_L and X_L and then decreasing the values of the load components R_L and X_L using the SVC composed of (TCR&FC) as well as SVC composed of (TCR&FC)in parallel with TSC are represented in Fig.16, Fig.17, respectively.

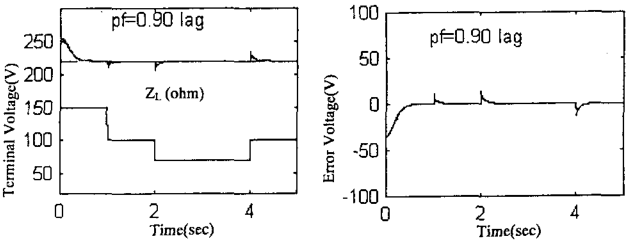


(a) Terminal voltage response (b) Terminal voltage error response

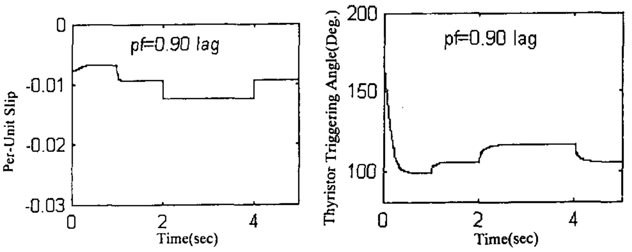


(c) Per unit slip response (d) Thyristor triggering delay angle response

Fig. 12 Single-phase SEIG performance responses using SVC composed of TCR and FC.

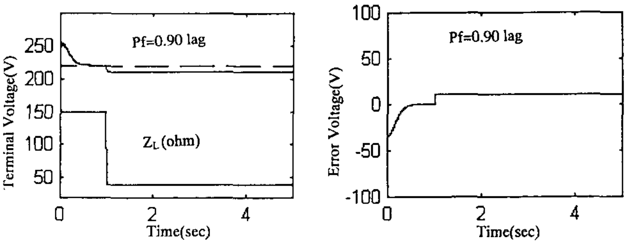


(a) Terminal voltage response (b) Terminal voltage error response

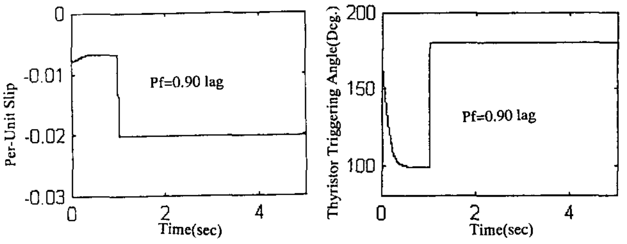


(c) Per unit slip response (d) Thyristor triggering delay angle response

Fig. 13 Single-phase SEIG performance responses using SVC composed of TCR and FC.

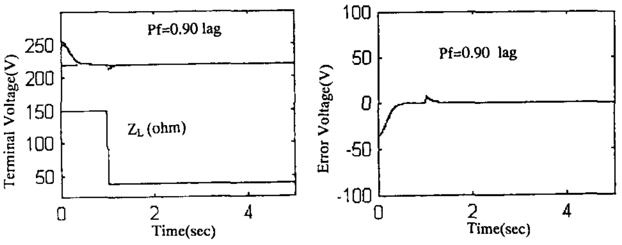


(a) Terminal voltage response (b) Terminal voltage error response

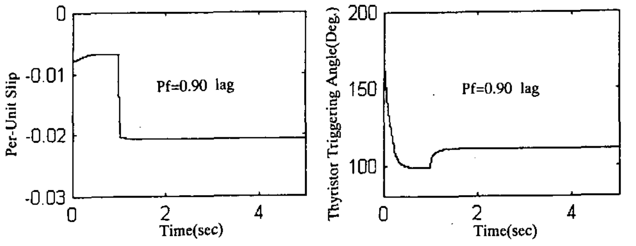


(c) Per unit slip response (d) Thyristor triggering delay angle response

Fig. 14 Single-phase SEIG performance responses using SVC composed of TCR and FC.



(a) Terminal voltage response (b) Terminal voltage error response



(c) Per unit slip response (d) Thyristor triggering delay angle response

Fig. 15 Single-phase SEIG performance responses using SVC composed of TCR and FC in parallel with TSC.

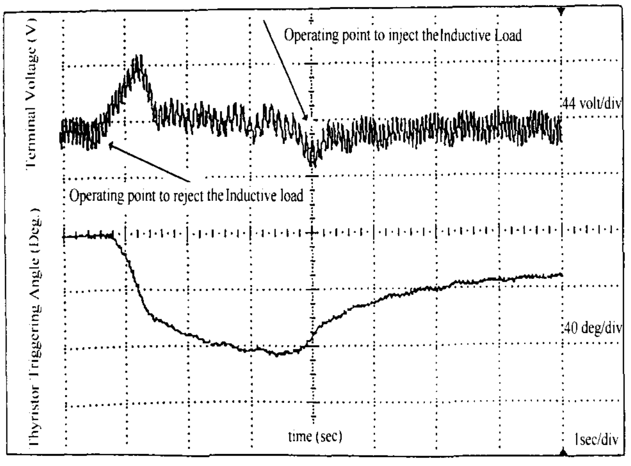


Fig. 16 Single-phase SEIG experimental terminal voltage and thyristor triggering angle responses in case of using SVC composed of FC and TCR under 0.9 lagging power factor load for load variations.

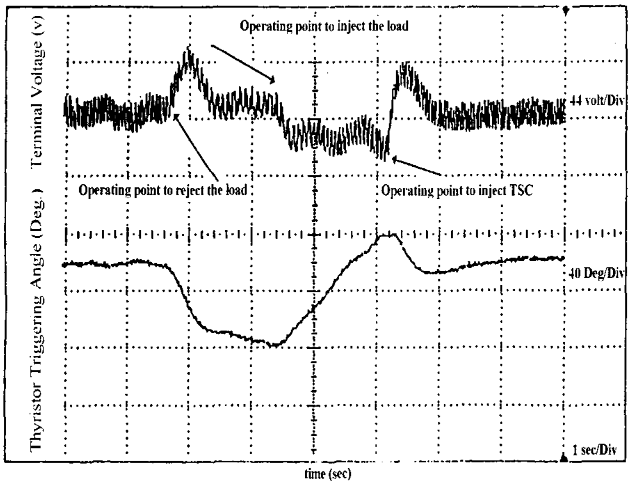


Fig. 17 Single-phase SEIG experimental terminal voltage and thyristor triggering angle responses in case of using SVC composed of FC , TSC under TCR and 0.9 lagging power factor load for load variations.

5. Conclusions

The present paper has introduced the simulation operating performance results of the single-phase SEIG evaluated by using the per-unit slip frequency state variable and compared with those obtained by using the per-unit frequency state variable. The comparative operating performance results have provided the close agreements between two steady-state analysis performance algorithms based on the electro-mechanical equivalent circuit of the single-phase SEIG. The above results have proved a good agreement between the characteristics of the single-phase SEIG obtained from the computer simulation and experimental results carried out for the single-phase SEIG. The coincidence of the experimentally obtained results and theoretical simulation results has proved the validity of the derived approach using the per-unit slip frequency state variable. Moreover, the PI controller-based feedback control scheme using the single-phase SVC composed of the FC in parallel with the TCR and the TSC was employed for the stable generated terminal voltage regulation of the single-phase SEIG loaded by different inductive loading conditions. A single-phase SEIG prototype setup was established for the low cost, ruggedness, reliable and simple control strategy in stable wind turbine driven power conditioner in the rural alternative energy effective utilization area from an earth environmental protection point of view. The feasible experimental results in the operating performances in the steady-sate of the single-phase SEIG have good agreements with those obtained from the digital simulation ones.

References

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

[2] A.K.Tandon, S.S.Murthy and G.J.Berg, "Steady State Analysis of Capacitor Self-Excited Induction Generator", IEEE Trans. on Power Advances Systems, Vol. PAS-103, No.3, pp.612-618, March, 1984

[3] 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

[4] 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.

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

[6] T.F.Chan "Analysis of A Single-Phase Self-Excited

Induction Generator", Journal of Electric Machines and Power Systems, Vol.23, pp.149-162, 1995.

[7] 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.

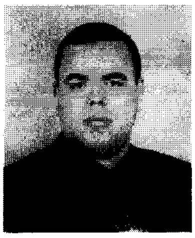
[8] S.P.Singh, M.P.Jain and Bhim Singh, "A New Technique for Analysis of Self-Excited Induction Generator", Journal of Electric Machine and Power Systems, Vol.23, pp.647-656,1995.

[9] 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.

[10] W. Koczara, " Variable Speed Three-Phase Power Generation Set", CD-Rom, EPE-2001, 2001.

[11] A. Koyanagi," Maximum Power Point Tracking of Wind Turbine Generator Using a Flywheel", Proceedings of the 2001 Japan Industry Application Society Conference, Vol.1, pp.395-398, 2001.

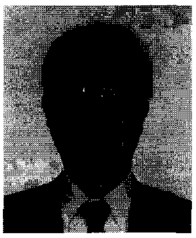
[12] IEEE Special Stability Controls Working Group Report, "Static VAR Compensator Models for Power Flow and Dynamic Performance Simulation ", IEEE Trans. on Power Systems, Vol.9, No.1, February 1994.



Tarek Ahmed

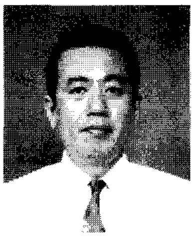
He received his M Sc.-Eng from the Electrical Engineering Department, Assiut University, Egypt in 1998. He is currently a Ph. D. candidate student in the Graduate School of Science and Engineering, the Power Electronic System and Control Engineering Laboratory at Yamaguchi University, Yamaguchi, Japan. His research interests are in the area of the new applications for the power electronic circuits and systems with the renewable energy and power systems and semiconductor power conditioners. Mr. Ahmed is a student-member of the IEEE and the Japan Society of the Power Electronics.

Tel: +81-836-85-9472 Fax: +81-836-85-9401



Osamu Noro

He received his M. Sc. in Applied Mathematics and Physics from Kyoto University, Kyoto, Japan. He is currently the manager of the Power Electronic Section, Development Department-1, System Technology Development Center of Kawasaki Heavy Industries Ltd., Akashi, Japan. His research interests are in the applications of systems technology consisting of the power electronics and electric machines such as turbine generator system, motor drive, electric and mechanical power conversion systems and so on. He is a member of IEEE and the Japan Society of Mechanical Engineers.



Koji Soshin

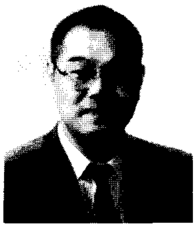
He received his M.Sc.-Eng from the Electronic Engineering Department, the Graduate School of Electrical and Electronics Engineering,. Kobe University, Kobe, Japan. He joined Matsushita Electric Works, Ltd. in 1979. He is interested in stepping motor applications, vector controlled inverter for the induction motor and power electronic circuits and systems technologies. He are now working in the power supplies for electric vehicle. He is now a Ph. D. candidate student in the Graduate School of Science and Engineering, Yamaguchi University, Yamaguchi, Japan. Mr. Soshin is a member of the Japan Society of Power Electronics.

Shinji Sato

He graduated from Mechanical Engineering, Technical Collage of Nigata East High School. He joined in the research project at Toshiba Corporation, Tokyo. After that, he joined in research and development of Sanken Electric, Co. Ltd. Saitama. He is now studying in the Power Electronic System Laboratory, the Graduate School of Science and Engineering, Yamaguchi University, Yamaguchi, Japan. His research area includes the soft-switching PWM rectifiers and DC-DC converters. He received the 2002 paper award in IEE-IAS-Japan. He is a member of Japan Society of System, Information and Control Engineers and Japan Society of Power Electronics.

Eiji Hiraki

He received his M. Sc.-Eng in Electrical Engineering from Osaka University, Osaka, Japan in 1990. He is currently with the Power Electronic System and Control Engineering Laboratory at Yamaguchi University, Yamaguchi, Japan, as a Research Associate. His research interests are in the soft-switching technique for high frequency switching power conversion systems. Mr. Hiraki is a member of IEE-Japan, the Japan Society of the Power Electronics and IEEE.



Mutsuo Nakaoka

He received his Dr-Eng. degree in Electrical Engineering from Osaka University, Osaka, Japan in 1981. He joined the Electrical and Electronics Engineering Department of Kobe University, Kobe, Japan in 1981. Since 1995, he has been a professor of the Electrical and Electronics Engineering Department, the Graduate School of Science and Engineering, Yamaguchi University, Yamaguchi, Japan. His research interests include application developments of power electronics circuit and systems. He received the 2001 premium paper award from IEE-UK and so on. Dr. Nakaoka is a member of the Institute of Electronics, Information and Communication Engineers of Japan, Institute of Illumination Engineering of Japan, European Power Electronics Association, the Japan Society of the Solar Energy, IEE-Korea and IEEE.