Novel Integral Cycle Voltage Controller for Self Excited Induction Generators

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***Abstract*-- This paper presents the theory of a new var regulator used for voltage control of self excited induction generators (SEIG). In this approach the excitation capacitors of each phase are switched individually by IGBTs at the zero crossing of respective capacitor currents, thereby eliminating switching losses and harmonics and reducing component count. Simulation results using Matlab–Simulink are presented and compared with experimentally obtained results. The developed integral control scheme presented here overcomes all the shortcomings of existing control schemes and, in addition to being self-starting is also capable of handling capacitive loads, thus making its application in standby generators acceptable with associated reduction in unit costs.**

***Index Terms*--Induction generators, Standby generators.**

I. Nomenclature

d^s, q^s d^r, q^r	stator and rotor direct and quadrature axes, respectively
k	number of pairs of poles
L^s,L^r	self inductance of stator and rotor coils, respectively
M^{sr}	mutual inductance between any pair of stator and rotor coils with their magnetic axes collinear
p	d/dt
R^l , L^l	load resistance in Ohms and Inductance in Henry
R^s, R^r	resistance of the stator and rotor coils, respectively
v_d^s i_d^s	stator voltage and current, respectively, associated with the d axis
v_d^r i_d^r	rotor voltage and current, respectively, associated with the d axis
v_q^s i_q^s	stator voltage and current, respectively, associated with the q axis.
v_q^r i_q^r	rotor voltage and current, respectively, associated with the q axis

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II. Introduction

THE induction motor operated as an induction generator with terminal capacitors, offers considerable advantages due to its ruggedness, low cost, brush-less squirrel cage rotor, manufacturing simplicity, low maintenance and wide off-the-shelf range as compared to the synchronous machine, but has a major drawback of poor voltage regulation. The rigid frequency and voltage of the grid makes the equivalent circuit model suitable for steady state analyses of the induction motor in the generating mode. However its analysis and operation as a stand-alone power source is complicated, since now both the voltage and frequency are variables, and involve solving non linear equations of higher order [1]. Under these conditions proper selection of equipment and the prediction of the system performance are essential for successful implementation of the scheme. The operation of such machine in any remote or stand alone conditions therefore requires some type of voltage regulator. Considerable literature exists describing various arrangement such as, contactor or thyristor switched capacitors, thyristor controlled inductors, saturable reactors, etc [2,3]. Devices like STATCOM in effect provide a virtual bus for the induction machine to operate. All these systems introduce a lot of harmonics or are expensive to build and complicated to program. The excitation capacitors too need to be sized properly for acceptable operation. The STATCOM based controller overcomes these problems but is not self-starting. The greatest drawback of most of the systems is their inability to handle unintentional capacitive loads as in the case of power factor improvement capacitors left on line, when the motor is disconnected by some fault, resulting in dangerous over voltages. To overcome these shortcomings which prevent the wide acceptance of induction generators in stand-alone engine-driven applications, the present controller was developed. The machine and load were modeled for dynamic analysis and simulation studies were carried out using MATLAB-SIMULINK. The encouraging results of the simulation were instrumental in building the hardware and technology demonstration setup reported here.

III. Dynamic Modeling and Simulation

Connection of excitation capacitors across the terminal can be represented in the d-q model of the machine as two additional equations with the capacitor voltages as state variables. Similarly the connection of the load across the terminal can be represented in two more equation shown here. The complete arrangement is shown in Fig. 1.

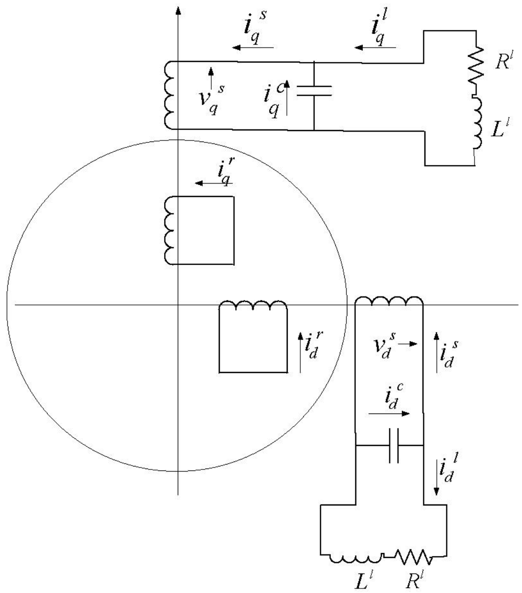

Fig. 1. d-q model of the induction machine complete with excitation capacitors and load.

Referring to Fig. 1 it is seen that

$$i_q^l = -i_q^s - Cpv_q^s \quad (1)$$

$$i_d^l = -i_d^s - Cpv_d^s \quad (2)$$

and

$$v_q^s = i_q^l \left(R^l + L^l p\right) \quad (3)$$

$$v_d^s = i_d^l \left(R^l + L^l p\right) \quad (4)$$

combining the above two equations in the standard d-q model[4] of the induction machine we get the dynamic model of a self excited induction generator complete with excitation capacitor and load, giving due representation to the capacitive voltages and inductor currents as state variable is in (5)

$$\begin{pmatrix} v_q^s \\ v_d^s \\ 0 \\ 0 \\ i_q^l \\ i_d^l \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} (R^s+L^s p) & 0 & M^{sr} p & 0 & 0 & 0 & 0 & 0 \\ 0 & (R^s+L^s P) & 0 & M^{sr} p & 0 & 0 & 0 & 0 \\ M^{sr} p & k\omega_r M^{sr} & (R^r+L^r p) & k\omega_r L^r & 0 & 0 & 0 & 0 \\ -k\omega_r M^{sr} & M^{sr} p & -k\omega_r L^r & (R^r+L^r p) & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & Cp & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & Cp & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & -(R^l+L^l p) & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & -(R^l+L^l p) \end{pmatrix} \begin{pmatrix} i_q^s \\ i_d^s \\ i_q^r \\ i_d^r \\ v_q^c \\ v_d^c \\ i_q^l \\ i_d^l \end{pmatrix} \quad \ldots\ldots.(5)$$

In order to investigate the acceptability of the proposed integral cycle control under extreme conditions, magnetic saturation is not represented. This approach will then also permit operation in the linear region of the saturation curve. Capacitance value Cp is selected to be greater than that required to achieve self excitation; Loading is controlled by varying R^l and L^l. Other variables in (5) being machine parameters. Since the capacitive vars absorbed by the machine is a function of the loading on the machine too, for low values of capacitance just above minimum required for self excitation, loading of the machine with resistive load only is sufficient to absorb the excess capacitive vars. By monitoring the line voltages and switching the terminal capacitors- switching operation being carried out only at current zero crossings- the machine model can operate in any average condition, i.e., of excess capacitive vars, deficient capacitive vars or just balanced condition corresponding to voltage build-up, voltage decay or stable voltage operation.

A. Simulation Results

Results of the simulation are shown in Fig 2. It shows the variation in line voltage over time while the capacitive vars are varied in a controlled fashion. The machine is driven at constant speed with no load and minimum required capacitance for self excitation. The exponential build up of terminal voltage on achieving self excitation is seen.

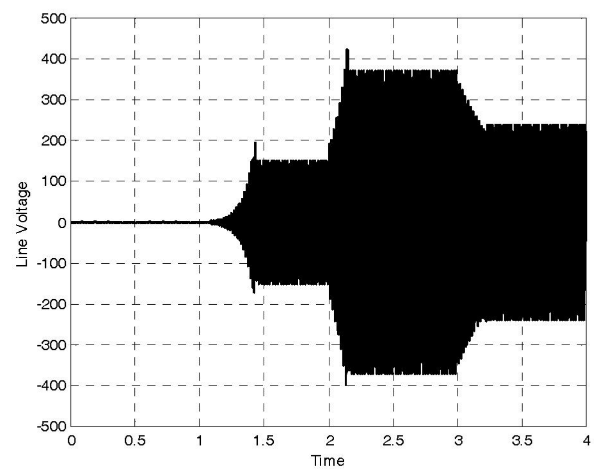

Fig. 2. Simulation results showing terminal voltage being controlled at desired values.

Referring to Fig. 2: At 1.4s the when the line voltage exceeds the set-point, control system is activated and the capacitors of switched off and on for integral number of cycle in the manner of 'duty cycle'. Upon change of the set-point, at 2s, the capacitors are fully on line and the voltage again rises until the new set-point is reached and the capacitor are again on integral cycle based 'duty cycle'. At 3s, when the line voltage set-point is reduced, the capacitors are switched off at their respective current zeros, until the voltage decays to the new reduced set-point, thus activating the control scheme and stabilizing the voltage.

IV. EXPERIMENTAL SETUP

The Schematic diagram of the implemented hardware set up in shown in Fig. 3. The capacitors are connected to the terminals through IGBTs. For cold starting, i.e., without the use of an external power source, a normally closed contactor (not shown) bypasses the IGBT's, connecting the capacitors directly across the terminal of the induction machine and providing a low resistance path for the extremely small excitation currents resulting from residual magnetism of the rotor and thus permitting voltage buildup. The contactor opens when the terminal voltage reaches 50% of rated voltage of machine which is sufficient to power up the control circuits.. Hall effect current and voltage sensors are used as isolation devices between power and control circuits.

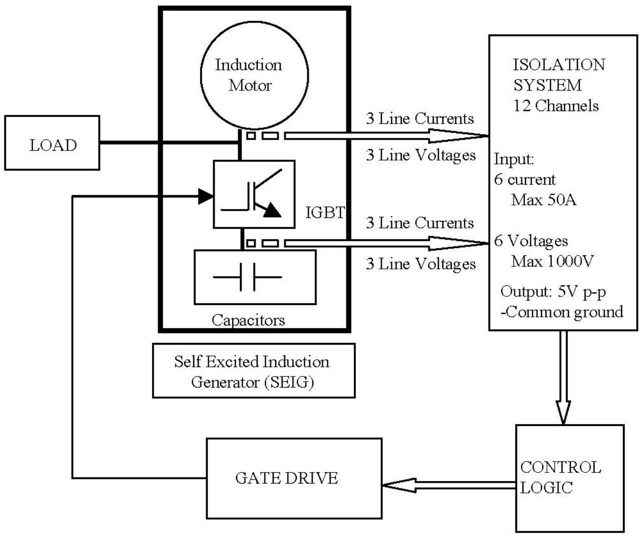

Fig. 3. Schematic diagram of experimental setup.

The Control logic is implemented using CMOS logic ICs. The control circuit monitors and compares machine terminal voltage with the set point. Switching of the capacitors on high or low voltage in each phase is implemented only at the zero crossing of currents, irrespective of the point at which the decision to switch takes place. The dead band between high and low voltage set-point is continually adjustable

Since switching is at zero currents, the device losses are considerably reduced, in addition the integral cycle switching scheme eliminates the need for snubber circuits, and accordingly none have been provided, resulting in reduced component count and complexity.

A. Experimental Results

The operation of the control scheme may be observed from Fig. 4, 5 and 6 which are Oscilloscope prints taken while the control system was in operation and the machine was loaded by R-L load. The top trace of all the three figures is the line voltage, the middle trace the line current and the bottom trace in the capacitor voltage. Fig. 4 shows the switching in and out of one bank of capacitors in a 'duty cycle' manner. The capacitor bank is on for a integral number of cycles and off for a integral no of cycles. The ratio between number of on cycles to number of off cycles depends on the loading of the machine and the dead-band between the high and low voltage set-points. The rise in line voltage while the capacitors are on line and fall in line voltage when the capacitors are disconnected may be observed in all there prints.

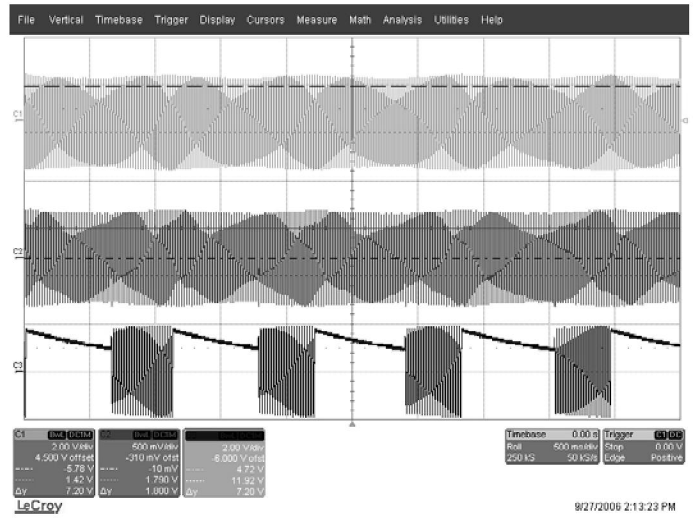

Fig. 4. Oscilloscope print showing 'duty cycle' base integral control action.

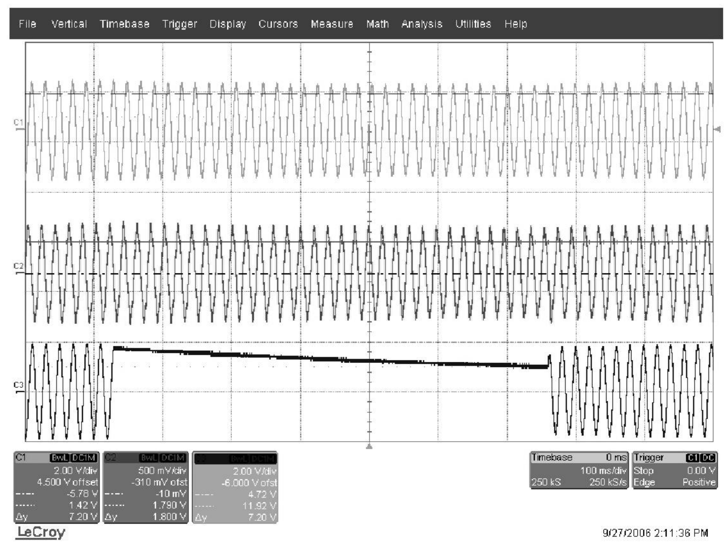

Fig. 5. Oscilloscope print showing Capacitor voltage during off state.

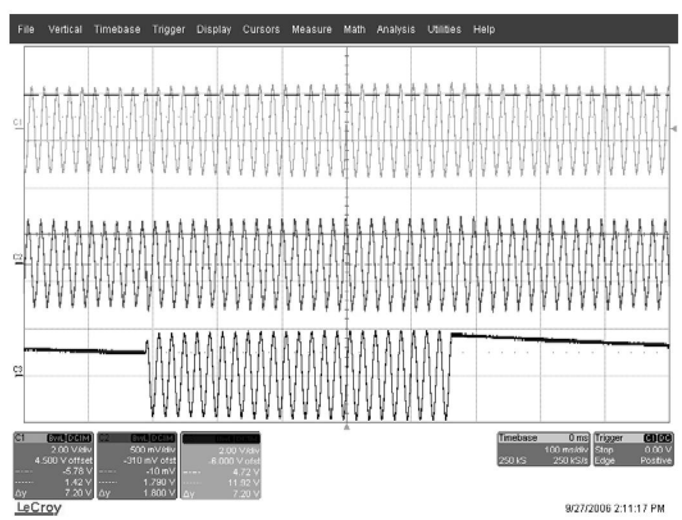

Fig. 6. Oscilloscope print showing capacitor voltage during on state.

Capacitor voltage during the off time is seen in more detail in Fig. 5, the droop in the capacitor voltage during this time is due to the discharge resistors connected across the terminals of the capacitors which should not be removed for safety reasons. The voltage across the capacitor during the on period may be observed in Fig. 6. The absence of switching surges in the traces of the line voltages in the three prints may also be observed.

V. Conclusion

A new control strategy that switches the excitation capacitors into or out of the circuit for integral number of cycles is presented. The effectiveness of this method is studied using the dynamic model and MATLAB-SIMULINK software, which confirm the same. A laboratory technology demonstration model is built and test results are presented. These show the control strategy if very effective in controlling the voltage at any desired value irrespective of the loading conditions. The inherent ability of the control to switch off the capacitors totally, effectively takes care of unintentional capacitive loading of the machine, thus demonstrating its capability to take care of any random loading without restriction, making it a suitable for standby generators.

VI. References

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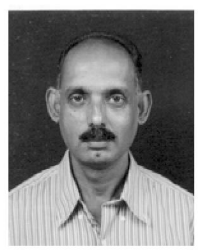
VII. Biographies

S.S. Murthy (SM' 87) was born in Karnataka, India, in 1946. He received his B.E., M.Tech. and Ph.D.degrees respectively from Bangalore University, Indian Institute of Technology (IIT) Bombay, and IIT Delhi. After serving a year at BITS Pilani, he has been with IIT Delhi as faculty since 1970 and professor since 1983. He has held several visiting Positions in India and Abroad such as: Visiting Fellow Univ. of Newcastle on Tyne (UK), Visiting Professor, Univ. of Calgary (Canada), Visiting Consultant, Kirloskar Elec. Co., Director, ERDA Baroda, Adjunct Prof. IISc Bangalore and Director of NITK, Surathkal He has published over 200 research papers in refereed journals and conferences, guided over 100 theses/dissertations at B. Tech., M. Tech,MS. and Ph. D. levels and completed over 80 sponsored research and industrial consultancy projects dealing with Electrical Machines, Drives and Energy Systems and sponsored by major electrical industries in India. Dr. Murthy has received many awards notable being-ISTE/Maharashtra Govt. Award for outstanding research, .IETE/Bimal Bose Award for contribution in Power Electronics and President of India prize for Best paper published in Journal of Institution of Engineers. In recognition of his outstanding professional contributions the prestigious Indian National Academy of Engineering (INAE) has conferred him as a Fellow of INAE. He is also a Life Senior Life Member of IEEE, Fellow of IEE, Life Fellow of the Institution of Engineers,(India), and Life Member of ISTE.



Aloysius Jude Pius Pinto (M' 96, Student 05) was born in Mangalore, India, on Jan 19, 1955. He graduated from the Karnataka Regional Engineering College, Surathkal in 1976. After working for 21 years went back to college and completed his masters degree in 1999 at the same institution. He is now working as a research/PhD scholar at National Institute of Technology Karnataka, India. His employment experience included Engineering, procurement, installation and commissioning of electrical systems for Power stations, Refineries and petrochemical plants both in India and middle east

Abdul Rahiman Beig (M'92) received the B.E. degree in Electrical and Electronics Engineering from National Institute of Technology Karnataka, Surathkal, India, in 1989. M.Tech. and PhD degrees in Electrical Engineering from Indian Institute of Science, Bangalore, in 1998 and 2004 respectively. He is currently an Assistant Professor in the Department of Electrical Engineering, National Institute of Technology Karnataka, Suratkal, India. From 1989 to 1992, he was with Kirloskar Electric Company, Ltd, Mysore, India, as a R&D Engineer in the drives group. His research interests include ac drives and multi level inverters. Dr. Beig received the Innovative Student Project Award for his Ph.D. work from the Indian National Academy of Engineering in 2000 and in 1998 L&T- ISTE National Award for the his M.E. thesis from the Indian Society for Technical Education.