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A Novel Variable-Speed Renewable-Energy Generation System of Induction Generator and PWM Converter for Small-Scale Hybrid Power Applications

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Abstract— **This paper presents a simple AC-DC power conditioner for a squirell-cage induction generator (IG) operating under variable shaft speeds. The necessary reactive power for the IG system is supplied by means of a capacitor bank and a voltage-source PWM converter. Using a capacitor bank to transfer the reactive power to the IG under the rated speed and no-load conditions starts the IG operation and reduces the PWM power converter size. A simple control compensating for changes in the electrical loads as well as the variation in speed was developed to regulate the voltages of the IG system by controlling the rotor flux through its reactive and active currents control implementation. This proposed power conditioning scheme can be used efficiently as a wind power generation system where the output voltage of the IG is maintained constant voltage despite the variable frequency and the DC bus voltage of the PWM converter can be used for either DC applications such as battery charging or AC power applications with 60 / 50 Hz by connecting a stand alone inverter. The experimental and simulated operating performance results of a 5 kW IG scheme at various speeds and loads are presented.**

Keywords: Induction Generator, Modeling and simulation, Vector Control, AC and DC Hybrid Power conditioner, PWM Converter

I. INTRODUCTION

For small-scale application of a stand-alone wind power conversion system, the induction generator (IG) must establish its output voltage and frequency where the speed is not constant and consequently poses a serious voltage problem[1-5]. Therefore it is necessary to develop a simple and low cost voltage regulation system. The regulated output voltage of IG can be directly connected to a load and equipment, which are non-sensitive to the AC frequency such as an electric heater or to a battery charger and super capacitor energy storage using a rectifier circuit cascaded with DC-DC converter to provide a specified DC output voltage.

The solution for the IG voltage regulation problem due to the load and/or the speed changes is associated with the need of a continuous supply of the necessary leading VARs instead of the existed fixed capacitor[6-9]. A wide variety of VAR generators with many control strategies using power electronic technology have been developed for the stand-alone IG[10-15]. Some of these proposals, which are based on a shunt-connected PWM voltage source inverter supplying reactive current to the IG and field-orientation algorithms to excite and control the IG with a stiff DC voltage regulation and high efficiency[10-13]. However, the PWM converter has to be designed for the rated power and the battery life will decrease due to high ripple currents if filter capacitors are not used. Moreover an additional decoupling compensation should be applied for vector control in stator flux orientation. Due to the increase of the electrical load demand in automobiles, an induction-machine-based automotive power generation scheme with a diode bridge rectifier and a PWM-VSI using rotor field orientation was proposed to control the output voltage of the diode bridge rectifier[14]. However, there is a serious voltage harmonics problem with this proposed system. To reduce the system cost and the rating of the PWM converter, a more reliable and simple method of starting the induction generator is to use the capacitor bank that can generate its output voltage. In this case, the capacitor bank and a PWM-VSI connected across the IG terminals via filter inductors supply the required reactive power to regulate both the AC and DC bus voltage.

II. SYSTEM CONFIGURATION

Figure.1 shows the block diagram of the controller for the proposed IG scheme. The IG is excited simultaneously by a capacitor bank with C = 150 μ F and a PWM converter. The generated electrical power of this proposed IG system is supplied to a DC and an AC load. The AC terminal voltage of the IG is kept under constant voltage despite the variable frequency and the DC-bus voltage of the PWM converter can be used for either a 60/50 Hz stand alone inverter or DC-DC converter. The IG is started using a capacitor bank, to minimize the PWM converter size. Therefore, the capacitor provides the rated reactive current needed to excite the IG while the PWM converter adds the reactive current required to regulate the IG output voltages. The filter inductor and the DC-bus capacitor are designed such that the converter maintains current control even at the maximum speed under rated load. The indirect-field-orientation control is used to compensate the current controllers for regulating the voltage on the DC-bus and the

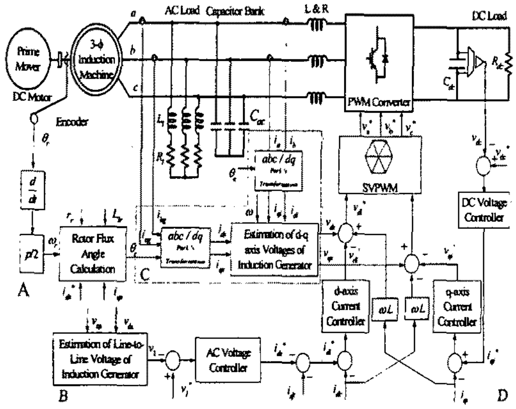
![fig1]

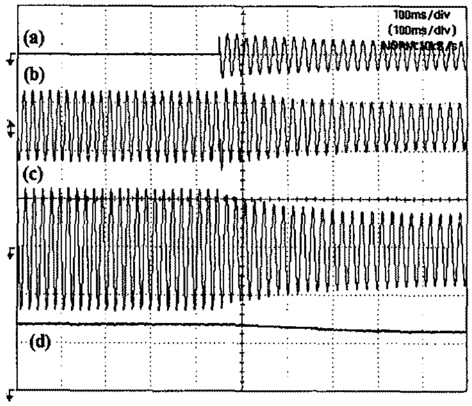
Fig.1 Induction generator for small-scale AC and DC power applications

terminals of the IG. The voltage across the DC-bus capacitor V_{dc} is measured and compared with the reference capacitor voltage V_{ref}, and the error voltage is fed to the proportional–integral controller (PI) to generate the q-axis current command i^{*}_{qs}. For proper AC voltage regulator current control, the IG output voltage v_l is measured and compared with a reference voltage V_{lref} and the error voltage is fed to a PI controller to generate the d-axis IG command current i^{*}_{ds}. The IG stator reactive current reference i_{ds}^{*} must be limited to avoid the induction machine saturation.

Since the frequency of the generated voltage can be changed because of the possible speed changes of the prime mover, detecting the electrical rotor angle θ_e is obtained by integrating the synchronous angular frequency which is the difference between the measured rotor angular frequency ω_r and the computed slip angular frequency ω_{sr}. This simple and reliable control method relies on knowledge of induction machine parameters such as magnetizing inductance L_m and τ_r, and the real values of which may be changing as the operating conditions change. In this control design, the effects of parameter variations are considered. The electrical rotor angle is then used for transforming the measured phase currents and voltages of the IG into the respective d- and q-axes components such as i_{ds} and i_{qs}.

A. Problem of IG without Voltage Regulation System

One of the serious problems with the IG is its poor voltage regulation. Fig.2 shows the dynamic experimental results of the stand-alone IG with only 150 μF excitation capacitance. The output power has been increased from no-load to 0.57 kW, with 1600-r/min. The line voltage of the IG has been dramatically decreased from 220 V to 130 V. It was also recognized during the experiment works, the output voltage of the IG will collapsed directly with a little increase of the load power which means the maximum power can be supplied from the strand-alone IG without voltage regulation is very small as compared with the rated power of the IG (10 % of the IG rated power). Fig.3 illustrates the simulated and experimental results of the steady-state line voltage and the speed of the prime mover (DC motor) against the output power of the IG with resistive load variation. Fig.3 proves the maximum power, which can be obtained from the IG with stable operation and 150 μF, is about 0.57 kW. The speed slightly changes with increasing the load power due to the electrical loading increase on the IG terminals. Therefore, the frequency variations can be easily recognized due to both the speed and the resistive load changes.



(a) Load current; (12.5 A/ div), (b) IG current; (12.5 A/ div),
(c) IG line voltage; (250 V/ div), (d) DC motor speed; (1100 (r/min)/ div)

Fig.2 Experimental results of stand-alone IG with capacitor bank due to load power variations from 0 -557 W

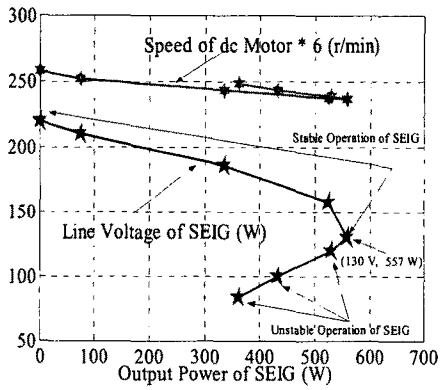


Fig.3 Steady-state line voltage of IG and speed of DC motor against resistive load power variations

B. IG With Voltage Regulation Scheme

The Matlab/Simulink environments have been used for designing the dynamic model of the proposed IG system shown in Fig.1 under various disturbances. In Figs. 4–9, the steady-state results of the IG system are depicted with the DC load changes from no-load to half-full-load (Pout = 2.5 kW) conditions within a per-unit speed range from 0.75 to 1.4. Fig. 4 shows the IG line voltage with the prime mover speed. The line voltage of the IG could not be regulated to the reference voltage; 200 V at low speeds and Pout = 2.5 kW, due to the limitation of the rated stator reactive current, i_{ds}=15.6 A and a voltage drop in the IG resistances and leakage inductances, caused by the active current, i_{qs}. However, the line voltage regulation is achieved at no-load. In Fig. 5, the IG stator reactive current against the prime mover speed is depicted. The stator reactive current reaches its rated value in an attempt to regulate the stator voltage at the low-speed range. For the high-speed range, the stator reactive current is below the rated value, allowing the controller to achieve IG voltage regulation. The obvious effect of increasing the DC load power and the prime mover speed on the synchronous angular frequency of the IG is also depicted in Fig.6. As shown in Fig7, the per-phase reactive current of capacitor bank depends on the regulated stator voltage and frequency. Therefore, any voltage drop due to the active current has to be compensated by the converter reactive current. Fig.8 shows the reactive current of PWM converter versus the rotor speed. At lower per-unit speeds than 1, the reactive current supplied from capacitor bank with C = 150 μ F is not enough for the IG system to reach the reference voltage, then an additional reactive current is required from the PWM converter (i_{dc} >0). On the other hand, at higher per-unit speeds than 1, the capacitor supplies more reactive current than that needed to reach the reference voltage, then the converter has to supply inductive current (i_{dc} < 0). Fig.9 shows the calculated excitation capacitance against the output voltage of the IG at no-load and synchronous speed (n = 1800 rpm). A 150 μ F capacitor, which is available in the laboratory, fits the excitation requirement of the IG at no-load. At no-load, the converter active current becomes negligible. Thus, the PWM converter has to be dimensioned taking into account the maximal reactive current only. As a consequence, for a narrower operating speed range, a smaller converter size can be used. For example, if the speed range is between 0.9 and 1.2 per-unit value , the maximum inverter current will be only 34 % of the rated current of the IG.

III. Simulation and Experimental Results of Proposed Voltage Regulation System

The simulation plot and experimental results obtained from a DSP-based PWM converter with a capacitor bank to excite and control the AC and DC voltages of the IG system are depicted in Figs.10 and 11, respectively. In these figures, the experimental responses of the phase current of the PWM converter (changed from 2.7 A to 7.7 A), the per-phase current of IG (changed from 6.1 A to 10.5 A), line voltage of the IG (constant line voltage; 200 V) and DC side voltage of PWM converter (constant DC voltage; 300 V) with a DC motor speed changed from 1530 rpm to 1450 rpm due to DC load power disturbances from no-load to half-full load; 2.5 kW. The designed control system successes to regulate the voltages of the IG system into the AC voltage reference 200 V and the DC reference voltage 300 V.

IV. Conclusions

The proposed system was shown to be able to feed AC and DC loads with a regulated, three-phase IG output voltage and DC-link voltage of PWM converter. There are several renewable energy applications for this system, such as micro wind and hydro power generation. The reactive power provided by both the capacitor bank and the PWM converter makes the system cost effective, robust and reliable. The control implementation under vector control scheme was demonstrated to be effective mean of supply a DC and an AC load with voltage regulation.

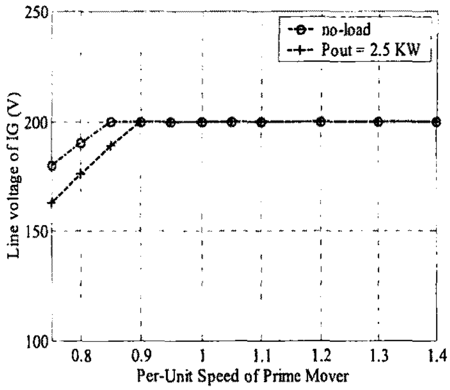


Fig. 4 Line voltage of IG versus per-unit speed of prime mover

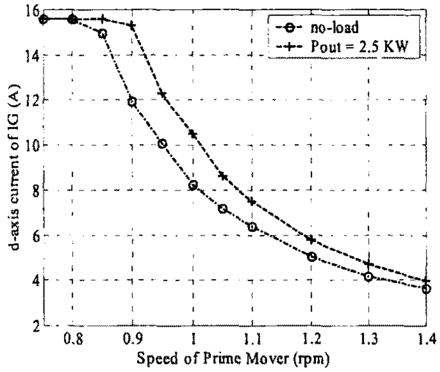


Fig. 5 IG reactive current versus per-unit speed of prime mover

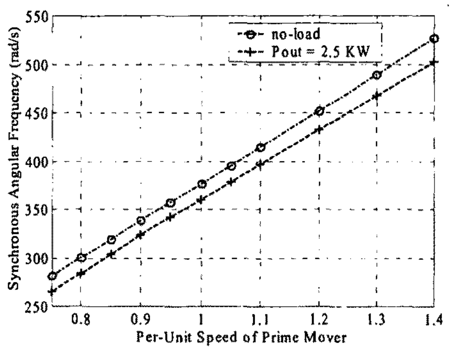


Fig. 6 Synchronous angular frequency versus per-unit rotor speed

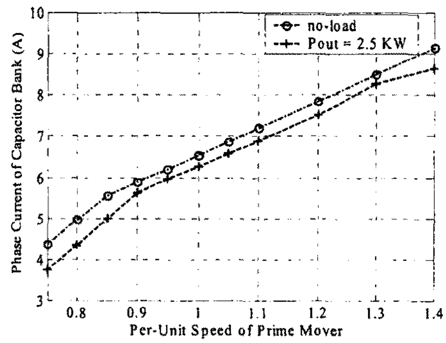


Fig. 7 Phase current of capacitor bank versus per-unit rotor speed

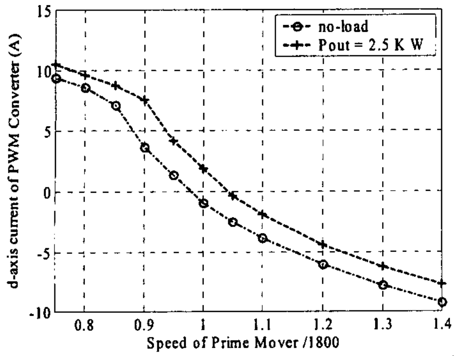


Fig. 8 Reactive current of converter versus per-unit rotor speed

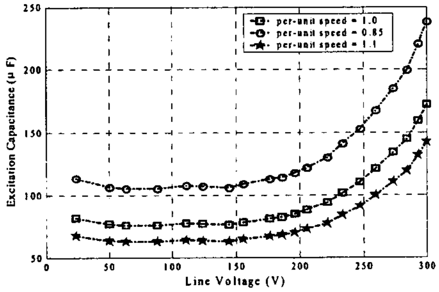
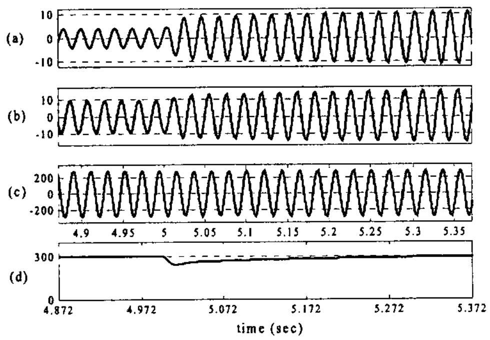
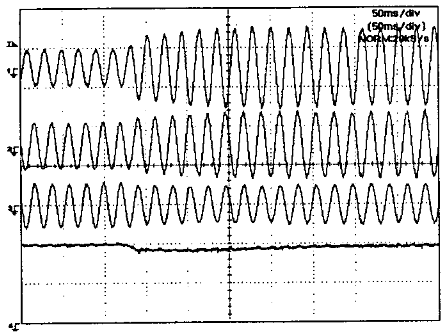


Fig.9 Excitation capacitance against line voltage of IM at no-load and different prime mover speeds



(a) PWM converter current (b) IG output current
(c) IG line voltage (d) DC-bus voltage

Fig.10 Simulation results of IG voltage regulation system due to DC load changes from no-load to half-full load; 2.5 kW



(a) Converter current (10 A/div) (b) IG output current (20 A/div)
(c) IG line voltage (550 V/div) (d) DC-bus voltage (150 V/div)

Fig.11 Experimental results of IG voltage regulation system due to DC power disturbances

Matlab / Simulink environments supported the control and analysis for the IG system and demonstrated that the voltage on the DC bus of PWM converter and the terminals of the IG can be regulated despite large changes in AC and DC loads and speed of the prime mover. Also, the voltage on the terminals of the machine was regulated so that a constant voltage could be supplied to an AC load. The experimental results are very promising and agree well with the simulation results. The output voltage regulation of the IG can be implemented by using the variable flux controller even with increase the speed of the prime mover, or load changes.

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