Dynamic modeling of self-excited induction generator driven by diesel engine with voltage and frequency regulation.

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***Abstract* – This work concerns an application of a three-phase cage induction machine (IM) as a self-excited generator connected to the AC side of a voltage-source pulsewidth modulation (PWM) bidirectional inverter. The generator is driven by a diesel engine that produces the mechanical torque necessary to keep the terminal voltage. An engine with renewable fuel, as methanol or vegetable oil, can be considered in this case. A good performance of the voltage regulation is obtained at the generator terminals by maintaining the voltage invariable at the capacitor in DC side (V_{dc}) of the VS-PWM inverter. It is then possible to employ V_{dc} as a feedback signal to control the prime mover speed. Simulated results demonstrate that the system presents satisfactory behavior at steady state and under load transients.**

***Keywords*: induction generator, self excitation, PWM inverter, voltage regulation, diesel engine**

I. INTRODUCTION

An externally driven induction machine (IM) can operate as an induction generator (IG) with sustained self-excitation when a suitable capacitor bank is appropriately connected across the stator terminals of the machine.

The use of cage induction machine as an IG has been increasing in the past few decades. The main advantages of this generator system are: low cost and less maintenance requirements, ruggedness, brushless construction, no need for synchronizing equipment, good over-speed capability, and inherent protection against severe overloads and short circuits.

Despite these favorable features, IM's are hardly employed as generators due to their unsatisfactory voltage regulation and frequency variation, even when driven under constant speed and feeding loads which consume active power [1], [2].

Due to the quick development of high-power semiconductor devices, most of the works on the studies of self-excited induction concentrate on design and voltage regulators in recent years [3], [4], [5], [6].

Diesel motors are the most efficient internal combustion engines. Smaller 4-stroke direct injection turbocharged motors can reach approximately 40% efficiency [7]. The rotation speed of a diesel engine depends on the amount of injected fuel and on the load applied to the engine crankshaft [8], [9], [10].

Diesel electrical aggregates are used in many situations: isolated electric power systems in remote places, plants where the electric provisioning is not enough for the peak demand; hospitals; etc. Positive characteristics are its compactness, the fast turn-on procedure, and the easy maintenance and operation. The diesel engine can be adapted for the operation with renewable fuels such as: biodiesel, methanol, straight vegetable oil (SVO) and biogas alone, or a mixture of biogas and diesel fuel.

The study developed in [11] presented a dynamic modeling of an ice-driven induction generator in which a DC motor driven by a power converter emulated the ICE. Here a prototype with diesel engine has been implemented (see Appendix).

The goal of this work is to analyze the use of induction generators as an alternative to substitute synchronous generators in low power diesel engine driven systems. The power limit for this scheme is related to the PWM inverter capacity and also with the dynamic system response that determines the design of some critical components, as the DC capacitor (C_{dc}). Simulated results employing a simple PID controller are reported and discussed.

II. SYSTEM CONFIGURATION

The cage induction machine as an IG is driven by a diesel engine that produces the mechanical torque necessary to keep the terminal voltage.

In the proposed system, the IG is excited by a three-phase capacitor bank (C_{ac}) and connected to the AC side of a PWM inverter through series inductance (L_f) as shown in Figure 1.

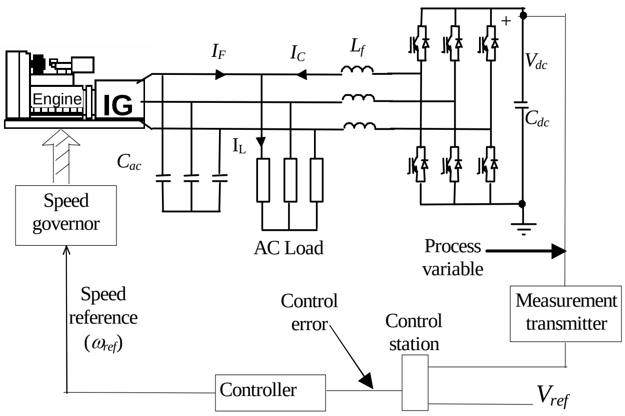

Fig. 1. IG-based system configuration.

The resulting L_f-C_{ac} filter attenuates the high frequency components produced by the inverter switching, ensuring IG terminal voltage with sinusoidal waveform.

The system startup is carried out through the IG self-excitation process. The self-excitation is the result of the interaction between the voltages provided by IG residual magnetic flux and the three-phase capacitor excitation bank (C_{ac}) which is dimensioned to make the process possible.

For the IG system, the generated power increases with the slip. Thus, the speed governor role is to set rotor speed so that the IG may produce enough power to supply the AC loads, as well as to keep C_{dc} properly charged. Consequently, the speed reference ω_{ref} is variable and proportional to the load power.

If the electric power produced by the IG is not sufficient to feed the load, the energy stored in C_{dc} will be used to supply the load, decreasing the DC voltage (V_{dc}). Otherwise, any exceeding power will be stored in C_{dc}. Thus V_{dc} is a suitable parameter to indicate the system power balance status and can be the feedback signal to the speed governor controller. The aim of the speed governor is to maintain V_{dc} constant on a reference value.

The speed governor is the injection diesel system, which is a component of the engine. Thus, the amount of diesel to be injected into the motor is proportional to the speed reference signal, as an electronic accelerator.

III. SYSTEM MODELING

In the proposed system, the induction generator is driven by a diesel engine, incorporating a control system, which adds many equations and variables to the system. The simulation studies have been carried out by using commercial transient simulation software Matlab/Simulink® system simulator [12]. Simulink does not have any domain-specific standard libraries, so a model for each component has to be developed. Add-on products extend the Simulink environment with tools for specific modeling. SimMechanics and SimDriveline, as well as SimPowerSystems, are part of Simulink Physical Modeling, encompassing the modeling and design of systems according to physical principles. Physical Modeling runs within the Simulink environment and interfaces with the rest of Simulink and with MATLAB. Unlike other Simulink blocks, which represent mathematical operations or operate on signals, Physical Modeling blocks represent physical components or relationships directly. SimPowerSystems uses electrical ports. The electrical ports handle both voltage and current, and the circuit is drawn in the same way as in a circuit diagram. SimDriveline is a set of block libraries and special simulation features for the engineering design and simulation of drivelines, or idealized powertrain systems, for use in the Simulink environment.

The generator model interfaces with the power electronics and controls components for dynamic system simulations. The IG is frequently represented by a conventional dynamic fifth-order model of IM in a two-axis d-q reference frame rotating at synchronous speed [12], [13]. In this work, the IG model implemented is based on the asynchronous machines with saturation curve block (SimPowerSystem library). The IM model block permits adding the induction machine parameters (according to table I) and also the inclusion of the saturation curve which is essential for modeling it as an induction generator.

The Diesel engine is a non-linear device. It presents dead-times, delays, non-linear behaviors making its control difficult. To simulate the complete dynamic of such a system it would be necessary a high order model. However, a detailed motor model is unnecessary to study the system response for fast speed perturbations, and a simpler model is enough [8]. Thus, the diesel engine model was extracted from SimDriveline library as shown in Figure 2. In the diesel engine block (Figure 3), it is possible to edit the engine torque curve for several speeds and to obtain the expected outputs.

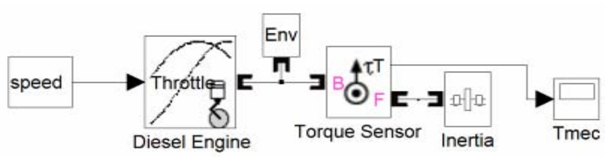

Fig. 2. Diesel machine system (full).

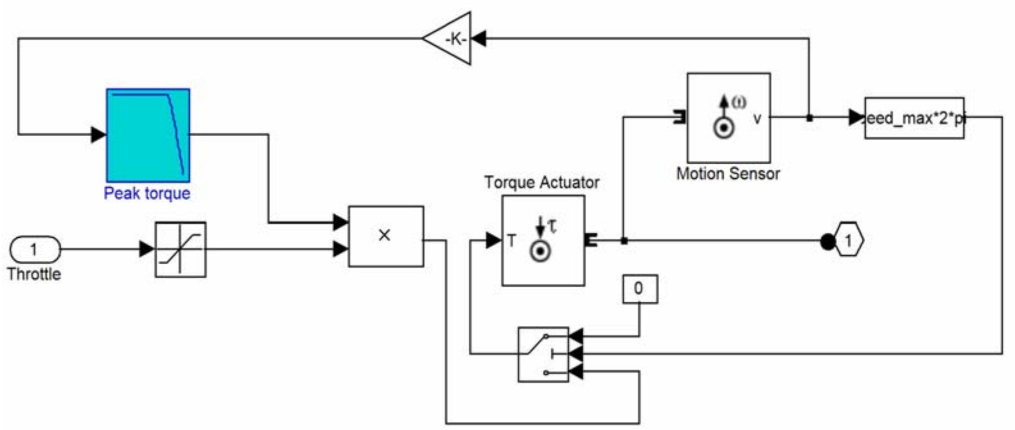

Fig. 3. Diesel engine subsystem.

TABLE I – System Parameters

Induction Generator 3,7 kW, 4 poles, 220 V, 60Hz		
Stator resistance	*rs*	*1.317* Ω
Rotor resistance	*rr*	*1.317* Ω
Stator leakage reactance	*Xls*	2.450 Ω
Rotor leakage reactance	*Xlr*	2.450 Ω
Mutual reactance	*Xm*	50.350 Ω
Fixed shunt capacitor reactance	*Xc*	*0.0565* Ω
VSI – PWM		
Coupling transformer and filter		
Inductance	L_f	*1.0 mH*
DC-link capacitance	C_{dc}	*10 mF*
Inverter DC-link voltage	V_{dc}	*320 V*

The generator system is also composed by an inverter (VSI-PWM), connected to the terminals of the induction machine through an inductor (L_f). The second-order low-pass filter composed of C_{ac} and Lf guarantees sinusoidal waveform at the IG leads. The assessment of C_{ac} is based exclusively on the IG self-excitation requirements.

The cutoff frequency (f_c) should be chosen one decade below the VS-PWM inverter switching frequency, to obtain a 40-dB attenuation for the voltage components at the switching frequency. L_f is then obtained by substituting C_{ac} and f_c in (1)

$$L_f = \frac{1}{(2\pi . f_c)^2 C_{ac}} \quad (1)$$

whose value calculated is presented in Table I.

After the start-up, the IG provides the energy required to charge C_{dc} and to supply the active losses. The PWM inverter control circuit is also fed by C_{dc} through a forward dc-dc converter.

The inverter is then enabled, and the fundamental frequency of the PWM inverter output voltage is maintained constant at 60Hz, yielding a constant frequency busbar at the IG terminals. As soon as the inverter is enabled, a transitory current appears, provoked by the instantaneous difference between generator and inverter terminal voltages, which is limited initially by the inductances series (L_f).

As the synchronous frequency of the IG is maintained constant by the inverter, the generated power is proportional to the rotor slip, depending, thus, on the diesel engine speed. To guarantee the generation of the necessary active power, the speed must be varied with load changes. For this reason, the DC voltage (V_{dc}), that indicates the power balance, is compared with the reference (V_{ref}) and the error is applied to a PID regulator (Controller in Figure 1), designed according to the Ziegler-Nichols method [14], [15], [16].

The complete arrangement of simulation used in the Matlab/Simulink® software tool is shown in Figure 4.

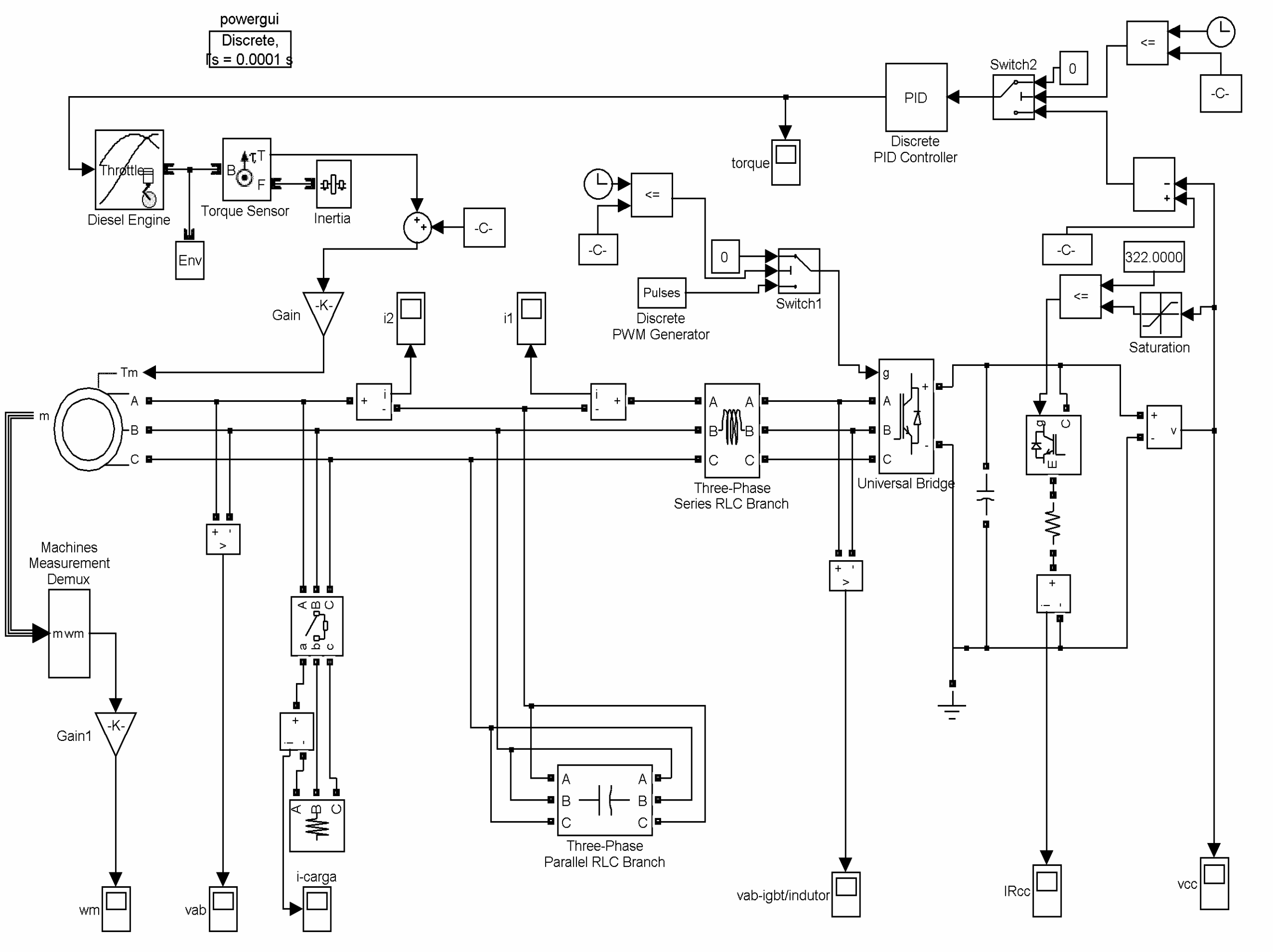

Fig. 4. Self-excited induction generator system driven by a diesel engine.

The system response to load variations was simulated and analyzed in order to determine the DC capacitance (C_{dc}) necessary to maintain the V_{dc} within an acceptable range [11]. Although a proportional–integral–differential (PID) regulator has been used, other compensators can be employed in the feedback dc-voltage loop. It was verified that, for one given power and using the correct adjustment of the PID, the dropping of the voltage bus (V_{dc}) it is inversely proportional to the C_{dc}. In this way, this value of C_{dc} will very become large as the power of the load increases.

Since the primer mover is not able to produce negative torque to break the rotor, a DC-link resistance (with hysteresis control) must be utilized to avoid over-voltages during AC-load disconnection. If the DC voltage becomes higher than a threshold , an IGBT connects the DC resistance in order to dissipate the energy.

IV. RESULTS

The IG-based system employing voltage control, presented in Figure 1, was simulated based on Matlab/Simulink® scheme shown in Figure 4. The IM parameters and the further values of the other components are presented in Table I.

Figure 5 presents the dynamic behavior of V_{dc} inverter voltage and the AC load current during load transients.

Figure 6 shows the dynamic behavior of V_{dc} during load transients, with and without hysteresis control. Since the purpose of the dc-link resistance is to avoid overvoltages under transient episodes, this does not operate under normal circumstances, when the nondissipative speed control is intended to maintain constant dc voltage.

Figure 7 illustrates the prime mover speed for different load steps. Notice that the speed governor increases the rotor speed, as AC load power enlarges, so that the IG may produce more power in order to satisfy the AC load demand.

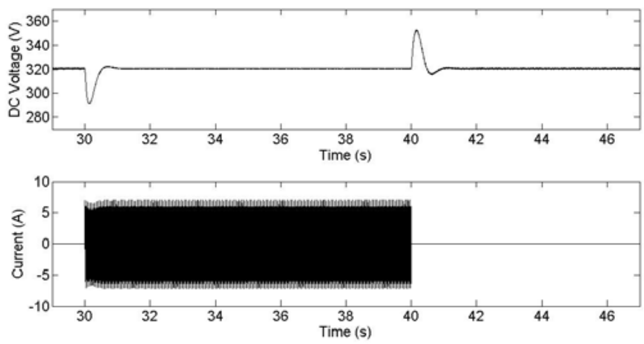

Fig. 5. V_{dc} inverter voltage and load line current.

V. CONCLUSION

In this paper an induction generator system driven by diesel engine with voltage and frequency regulation was presented and analyzed. The system has been modeled to study the control strategy necessary to regulate the diesel engine speed for compensating the load variation effects.

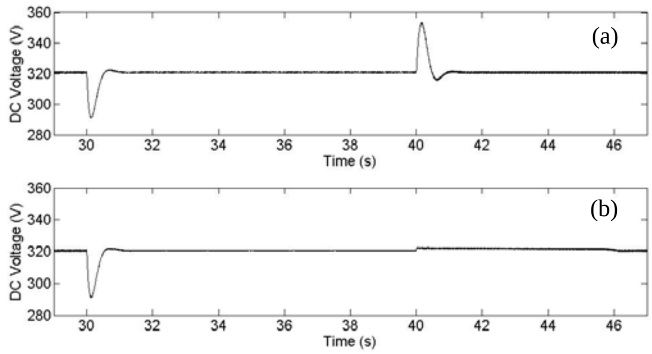

Fig. 6. V_{dc} inverter voltage during load transients: (a) without and (b) with hysteresis control.

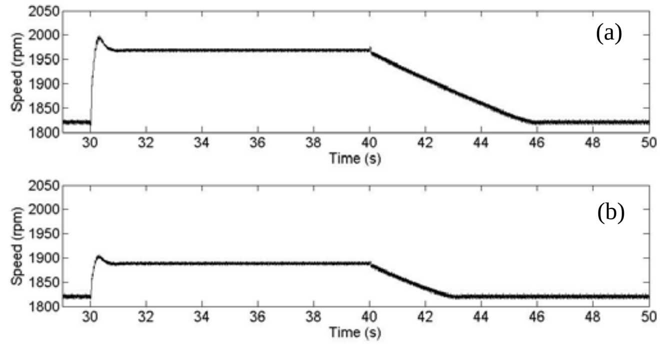

Fig. 7. Prime mover speed (rpm) for load of: (a) 1900W; (b) 900W

The PWM inverter DC voltage control (V_{dc} control), exerted by the injection fuel system (which is a component of the engine) seemed to be a reliable technique to obtain power balance and to adjust the amplitude of the terminal voltage.

Simulated results appear to be a good alternative of energy stand-alone source. A prototype has been partially implemented.

VI. ACKNOWLEDGMENT

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APPENDIX

Figure A1 shows the partially experimental arrangement implemented.

The phase-to-phase voltage during a typical run up is shown in Figure 6. The generator initially runs at 1800 rpm and the delta capacitor bank starts as indicated in the figure A2 (switch-closed).

Fig. A1. The experimental arrangement

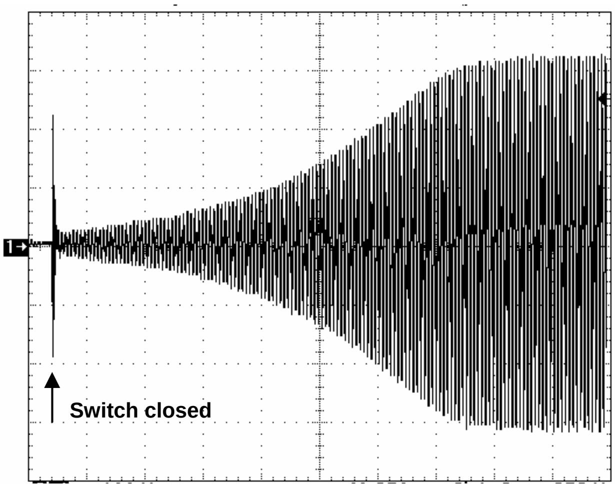

Fig. A2. Phase-to-phase voltage during self-excitation transient at 1800 rpm (100 V/div.). Time: 250 ms/div.

Figure A3 shows the no-load terminal voltage obtained through the generator system (Figure A1).

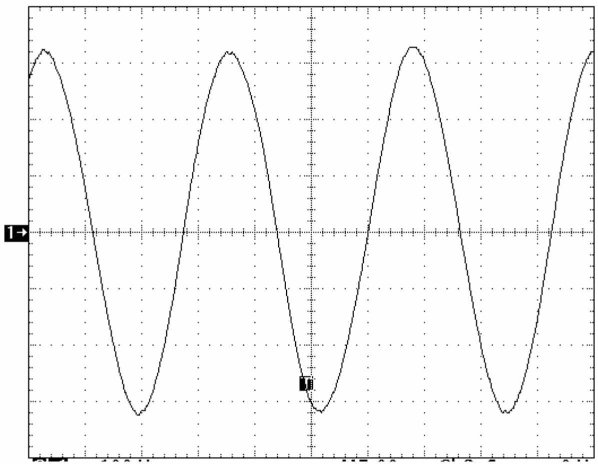

Fig. A3. AC Voltage (100 V/div.). Time: 5 ms/div.