Frequency and Voltage Regulation of Induction Generator Driven by Internal Combustion Engine

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***Abstract* – In many situations, internal combustion engine driven generators are used to produce electricity. Environmental concerns and the ever-increasing energy demand impulse the search for alternative energy sources. The engines with renewable fuel, as methanol or vegetable oil can be considered in this case. This paper presents an investigation of a self-excited induction generator driven by internal combustion engine with adjustable speed. The operating principles, theoretical analysis, computer simulations and experimental results are included in the paper. Both, simulated and experimental results demonstrate that the system presents satisfactory behavior at steady state and under load transients.**

I. INTRODUCTION

Environmental concerns and the ever-increasing energy demand impulse the search for alternative energy sources. In this context, it receives special attention the harness of small-scale energy sources as wind, solar, small hydro-plants and internal combustion engines.

The so-called Generating Groups (GG) are designed for autonomous production of electricity. These equipments present as main components the internal combustion (IC) engine (usually a Diesel motor, but the fuel could be a renewable fuel, as methanol or vegetable oils), the generator, and the supervision and control unit.

They are used in many situations: places without electricity network; plants where the electric provisioning is not enough for the peak demand; hospitals; etc. Positive characteristics of a GG are its compactness, the fast turn-on procedure, and the easy maintenance and operation.

Usually the generator is a synchronous machine. Synchronous generators are reliable sources of regulated three-phase constant frequency voltage, since the dynamic response of the speed governor be able to maintain constant rotor speed for any load power condition. However, they are expensive machines due to the maintenance required by its excitation system, which attains slip rings, brushes and field current control circuit.

It is frequently stated that squirrel-cage induction machines (IM) have robust construction, low maintenance cost and high power-weight ratio (W/kg). In addition, they are less expensive compared with DC and synchronous machines.

An externally driven induction machine 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. Although IGs have many favorable features, in the past, they were hardly employed due to its unsatisfactory voltage regulation and frequency variation, even when driven under constant speed.

Recently, they have become popular due to the suitability of these generators for various applications such as wind and small hydroelectric (micro-hydro) energy conversion. Great efforts have been carried out to overcome the drawbacks of the induction generators by applying power electronic converters and machine control techniques [3–6].

It was shown that it is possible to accomplish regulated three-phase voltage with constant frequency from the association of a three-phase IG with a three-phase voltage fed PWM bi-directional inverter [7,8].

A good voltage regulation is obtained at the generator leads by maintaining the voltage invariable at the capacitor in DC side (V_{dc}) of the VS-PWM inverter. It is also possible to employ V_{dc} as a feedback signal to control a prime mover with speed governor [8].

The aim of this paper is to discuss the use of induction generators as an alternative to synchronous generators in low power, IC engine driven systems. The power limit for this approach is related with the PWM inverter capability and also dynamic system response that determines the design of some critical components, as the DC capacitor.

Simulated results employing a simple PI controller are reported. Experimental results obtained from a 3 HP system are shown to validate the proposed method.

II. SYSTEM CONFIGURATION

The proposed system is mainly composed of an induction generator excited by a three-phase capacitor bank (C_{ac}) and connected to the AC side of a voltage-fed-PWM inverter through series inductance (L_f). The resulting L_fC_{ac} filter attenuates the high frequency components produced by the inverter switching, ensuring IG terminal voltage with sinusoidal waveform.

A speed governor controls the IG rotor shaft speed. Fig.1 presents the system configuration.

The main goal of this structure is to feed the AC load with satisfactory energy quality, which stands for providing three-phase balanced voltages, with constant frequency, sinusoidal waveform and regulated amplitude.

The prime mover is an IC motor; the speed regulator is the injection fuel system, which is a component of the motor. Thus, the amount of fuel to be injected into the motor is proportional to the speed reference (ω_{ref}) signal, as an electronic accelerator [8].

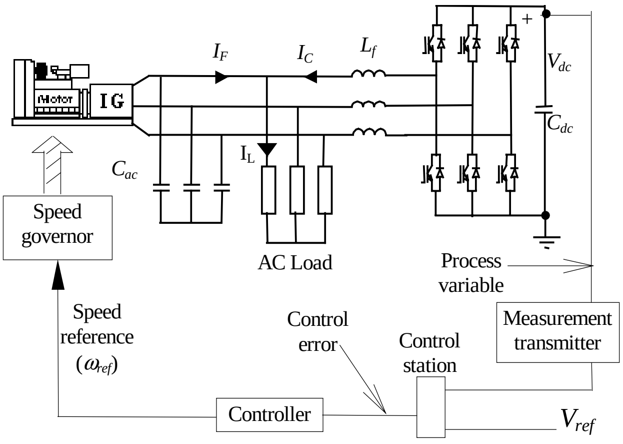

Fig. 1. IG based system configuration.

The fundamental frequency of the PWM inverter output voltage is maintained constant at 60Hz, yielding a constant frequency busbar at the IG leads.

At the DC side of the inverter there is not a power source, but only a capacitor. In case of power deficit (consumed power is higher than the generated power), the energy stored in C_{dc} supplies the load, reducing its voltage. Case the produced power is superior to the consumed one, the excess is stored in C_{dc}, increasing V_{dc}. This way, any variation in the power balance reflects in V_{dc}.

As the synchronous frequency of the IG is maintained constant by the PWM inverter, the generated power is proportional to the rotor slip, thus it depends on the IC motor speed.

The speed control regulates the power balance and consequently the voltage. This way, the system control strategy establishes a connection between the load active power and the voltage. Since the line voltage is maintained constant, the system automatically compensates for reactive power demand.

III. System Modeling

A. Induction Generator

Fig. 2 shows the arbitrary reference-frame d-q axis equivalent circuit for a thee-phase, symmetrical, induction machine when a capacitor bank and a resistive load are properly connected at the stator terminals.

When performing stability or transfer function analyses, it is convenient to analyze the system in a reference frame that rotates around the airgap in synchronism with the stator MMF at a speed corresponding to stator excitation frequency (imposed by the converter VS-PWM).

Machine voltage, flux, and current become constant quantities at steady-state operation. These systems equations represented in the synchronous rotating frame can be readily linearized around a particular steady-state operating point. The voltage equations [9, 10, 11] can be written as:

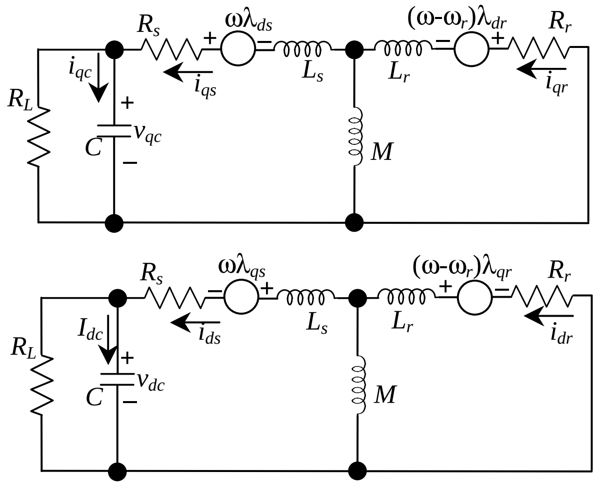

Fig. 2. d-q equivalent circuit of an induction generator

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + pL_s & \omega L_s & pM & \omega M \\ -\omega L_s & R_s + pL_s & -\omega M & pM \\ pM & (\omega-\omega_r)M & R_r + pL_r & (\omega-\omega_r)L_r \\ (\omega_r-\omega)M & pM & (\omega_r-\omega)L_r & R_r + pL_r \end{bmatrix} . \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (1)$$

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right) M \left(i_{qs} i_{dr} - i_{ds} i_{qr}\right) = T_L + B\omega_r + \frac{2J}{P}\left(p\omega_r\right) \quad (2)$$

In the equations (1) and (2) p is the operator *d/dt*, ω is reference angular speed, ω_r is the equivalent electric angular speed of the rotor. The parameters R_s e R_r are the stator resistance, and the rotor resistance referred to the stator side, respectively. The quantities L_s, M and L_r are the stator self-inductance, the mutual, and rotor self-inductance referred to the stator, respectively. P is the number of poles of the machine; J is the inertia of the rotor; B is the viscous friction and T_L is the load torque. These equations correspond to the operation as motor. For the operation as generator it is enough to consider the load a negative torque.

The equations of the excitation capacitor are:

$$\begin{bmatrix} i_{qc} \\ i_{dc} \end{bmatrix} = \begin{bmatrix} pC & \omega C \\ -\omega C & pC \end{bmatrix} . \begin{bmatrix} v_{qc} \\ v_{dc} \end{bmatrix} \quad (3)$$

The following assumptions are made for the analysis of the self-excited induction generator: 1) rotor variables are referred to the stator; 2) all parameters of the machine can be considered as constant except the magnetizing inductance M, whose value depends on the degree of the magnetic saturation. It is a nonlinear function of magnetizing current; 3) core losses in the excitation branch are neglected; 4) machine is spatial and time harmonic effects free.

B. Diesel Engine and Governor

In the following, the IC engine is supposed to be a Diesel motor. The fuel can be any kind of adequate combustible oil, as a vegetable oil.

Diesel motors are the most efficient internal combustion engines [12]. Smaller 4-stroke direct injection turbocharged motors can reach approximately 40% efficiency. Large low-speed 2-stroke engines achieve over 50% efficiency and can be fueled with low quality liquid hydrocarbons. It is interesting to notice that the technically realizable Diesel cycle does not differ substantially from the thermodynamically ideal one. The rotation speed of a Diesel motor depends on the amount of injected fuel and on the load applied to the engine crankshaft. The governor is a mechanical, electromechanical, or electronic device, used in all the Diesel motors to ensure the automatic control of the fuel injection in function of the load. It acts in the acceleration mechanism supplying fuel without abrupt variations and responding softly to load variations.

A comprehensive mathematical model is difficult to obtain because the Diesel motor is a non-linear device. The motor presents dead-times, delays, non-linear behaviors making difficult its control. To simulate the complete dynamic of such a system it would be necessary a high order model. However, a detailed motor model is unnecessary [13] to study the system response for fast speed perturbations, and a simpler model is enough [14]. A simplified general functional block diagram for a Diesel engine and the respective speed regulator system is shown in Fig. 3 [15, 16].

Referring to Fig. 3, the Actuator controls the fuel injection rate (Φ). Its dynamic behavior can be approximate by a first-order model, with a time constant τ_2. This time constant is a function of the oil temperature.

The engine is represented by a gain K_1 and a dead-time of combustion τ_1. The engine comprises a combustion system that produces the torque T_E as a function of the fuel flow (Φ). Any difference between T_E and load torque, T_L accelerates the combined inertia J. K_3 is a gain that adjust the control signal in order to drive the actuator.

A very significant feature of a Diesel engine, from the control point of view, is the discontinuous manner in which power is produced owing to the sequential firing of a relatively small number of cylinders [17].

This feature is important for two reasons:

a), it means that there is a time delay between the action of the governor that changes the fuel rate and the response of the engine to that change.

b) the engine crankshaft does not rotate at a uniform speed but rather experiences a cyclic variation in torque that gives rise to a cyclic speed variation.

A sensitive governor will respond to these cyclic speed variations and exhibit a small rhythm movement (jiggle) at its output. Such movements are very undesirable because of the wear induced in the governor and fuel pump mechanism, and normally have to be filtered out in the governor drive.

The effective firing delay can be approximately given by the actual time between consecutive pistons arrivals at the injection point plus a quarter of a the crankshaft revolution.

$$\tau_1 = \frac{60s}{2Nn} + \frac{60}{4N} \tag{4}$$

Where s = 2 or 4 for two or four-stroke engine; N= speed in rev/min and n= number of cylinders. This dead time is included in the transfer function. The open loop transfer function is:

$$H(s) = \frac{K}{s(1+\tau_2 s)} e^{-\tau_1 s} \tag{5}$$

The typical set of per unit values [14] used in the simulations is shown in Tab. I.

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 produces enough power to supply the loads, the system losses and the control circuits, as well as to keep C_{dc} properly charged.

In the present case, the rotor speed has to be set to match the IG power requirements, conversely to synchronous generator systems in which the rotor speed has to be kept constant. Consequently, the governor speed reference value is variable. The reference of speed (ω_{ref}) is variable and the rotor speed is proportional to the load power.

Typically, IG “slip” will range from about 10 rpm to as much as 50 or 70 rpm.

TABLE I
PARAMETERS FOR SIMULATION

Parameter	Value (pu)	Definition
K1	0.8-1.5	Engine torque constant
K2	1.0	Actuator constant
K3	1.0	Current driver constant
J	0.5	Plant and flywheel inertial constant
τ1	0.0-0.25	Engine dead-time
τ2	0.05-0.2	Actuator time constant

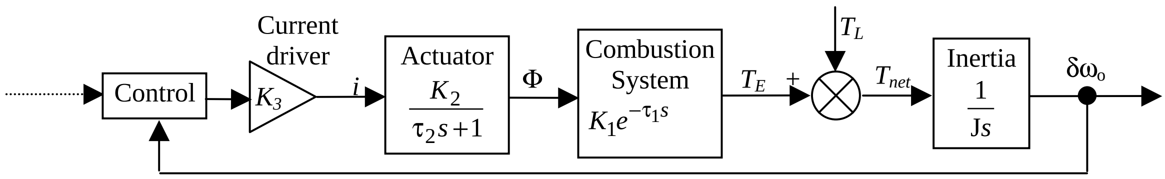

Fig. 3. Diesel engine - governor model

C. Power balance

In case of 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, thus decreasing the DC voltage. Otherwise, any exceeding generated power will be stored in C_{dc}. Thus, V_{dc} is a suitable parameter to indicate the system power balance status. Consequently, this voltage can be used as the feedback signal to the speed governor controller. The ultimate aim of the speed governor is to maintain V_{dc} constant on the reference value.

Neglecting the losses, power balance occurs when the generated power (P_g) is equal to the power drawn by the load (P_L). The stored energy variation in the capacitor is:

$$\Delta\varepsilon = \int \Delta P = P_g - P_L \tag{6}$$

The total energy variation is:

$$\Delta\varepsilon = \frac{1}{2}C\left(V_f^2 - V_i^2\right) = C\frac{\left(V_f + V_i\right)}{2}\Delta V = C\cdot\overline{V}\cdot\Delta V \tag{7}$$

Thus, the variation of the capacitor voltage is:

$$\Delta V = \frac{\Delta\varepsilon}{C\cdot\overline{V}} \tag{8}$$

IV. Simulation Results

The system, including the important variables used for simulation, is presented in Fig. 4. The setup used in SIMULINK simulation is shown in Fig. 5. The induction machine parameters are presented in Table II, and C_{ac} = 109.5 μF; C_d = 3 mF; L_f = 10 mH. The non-linear relationship between M (H) and the magnetizing current is determined by experimental tests, as shown in Fig. 6.

As for the experimental setup a DC motor will be used instead of the diesel motor, its model was used in the simulation. The DC motor drive system can be adjusted in order to emulate the diesel machine behavior.

The Figs. 7 and 8 show the dynamic behavior of V_{dc}, the AC load current, the DC motor armature current (proportional to the developed torque) and the speed during load transients.

The V_{dc} control revealed to be able to maintain the system power balance and the IG terminal voltage.

TABLE II
IG PARAMETERS @ 60 HZ.

Stator Resistance (R_S)	2.9554 Ω
Rotor Resistance (R_r)	1.9557 Ω
Leakage stator reactance (X_S),($120\pi L_s$)	3.6247Ω
Leakage rotor reactance (X_r), ($120\pi L_r$)	3.8214 Ω
Linkage reactance (X_m) ($120\pi M$)	80.087 Ω
Iron and mechanical losses resistance (R_m)	2125.9 Ω
Rated power	3 CV
Number of poles (P)	4
Rotor inertia (J)	0.0067 kg.m^2

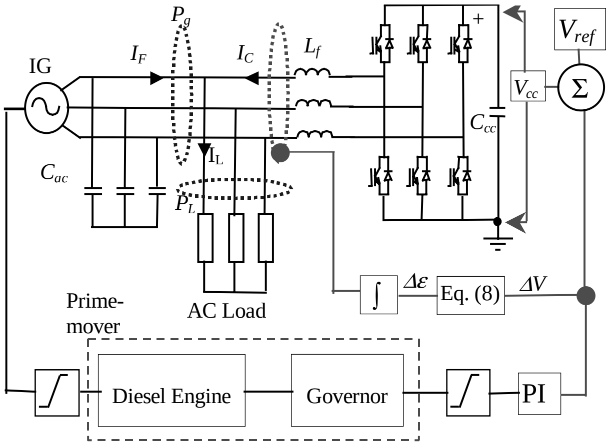

Fig. 4. – IG system including the control blocks.

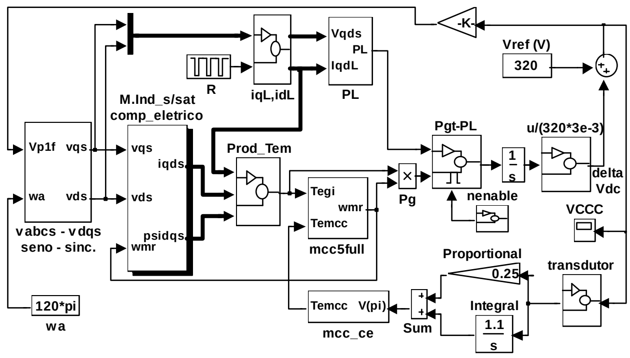

Fig. 5. Schematic of simulation setup in Simulink

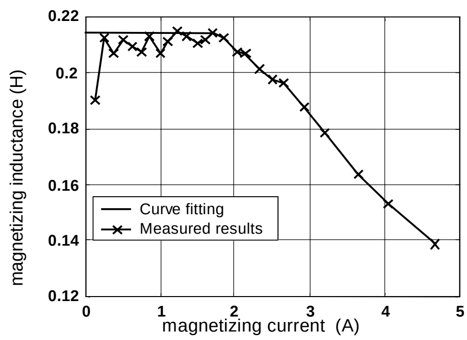

Fig. 6. Relationship between M (H) and the magnetizing current

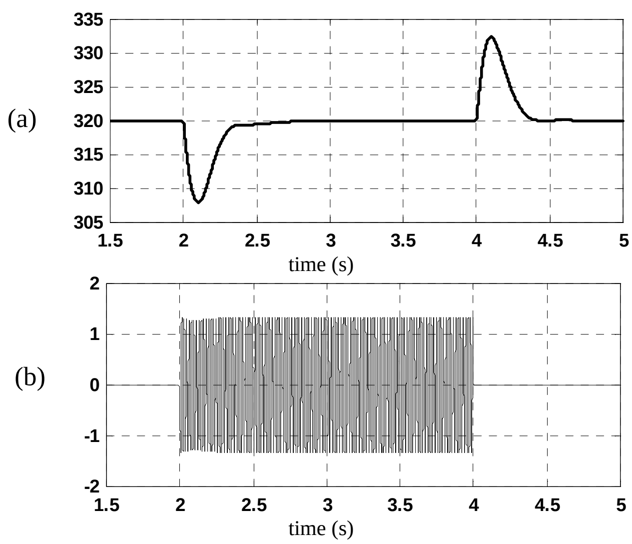

Fig. 7. (a) V_{dc} voltage [V] and (b) load line current [A].

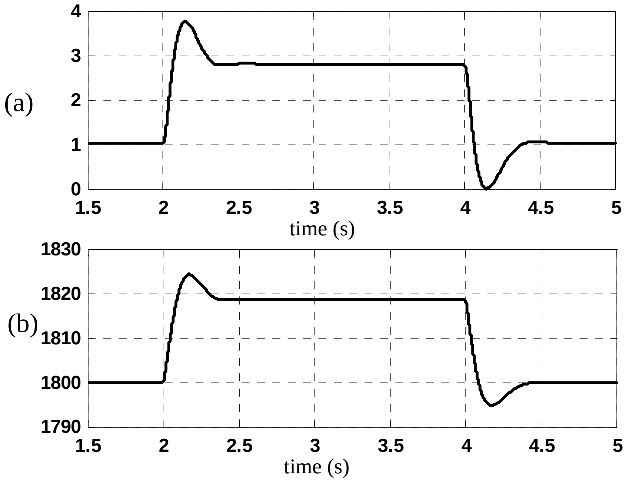

Fig. 8. (a) Dc motor armature current [A] and (b) speed [rpm].

V. Experimental Results

A three-phase induction generator setup was assembled to verify the operation of the IG system with the proposed control strategy. The diagram of the experimental arrangement is shown in Fig. 9. A DC motor emulates the diesel motor behavior.

The induction machine used as generator has the following nominal characteristics as motor: 3 HP, 220 V, 60 Hz, 4 poles, delta connection and the other parameters are described in the Table II.

The IG is connected to a commercial PWM inverter that was set up to produce 60 Hz and 220V. The switching frequency is 2 kHz.

The IG startup was obtained though by the self-excitation due to the interaction between the residual rotor flux and C_{ac}. Since the primer mover is not able to produce negative torque to breaking the rotor, for security purposes a resistor with hysteresis control was connected at the DC link to avoid over voltages during the disconnection of the AC-load.

The DC motor, that drives the IG, has constant field voltage. The armature voltage is controlled according to the variation of the DC link voltage (V_{dc}), developing the torque in accordance with the load.

For these tests the load was a light bulbs bank, with adjustable power.

Fig. 10 shows a load transient without speed correction, resulting in a AC voltage reduction due to the DC link voltage variation.

Fig. 11 shows a load transient with regulated primer-mover. The dynamic of the speed controller demonstrated to be stable and effective during load step transients. The DC side capacitance, together with the system dynamic response determines the voltage sag.

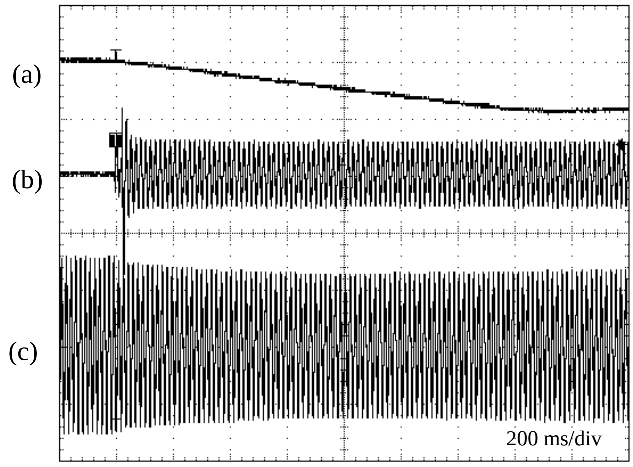

Fig. 10. a) V_{dc} Voltage (50 V/div.), b) AC load line current (2 A/div.) and c) IG terminal line voltage (200 V/div.) during load transient without speed correction.

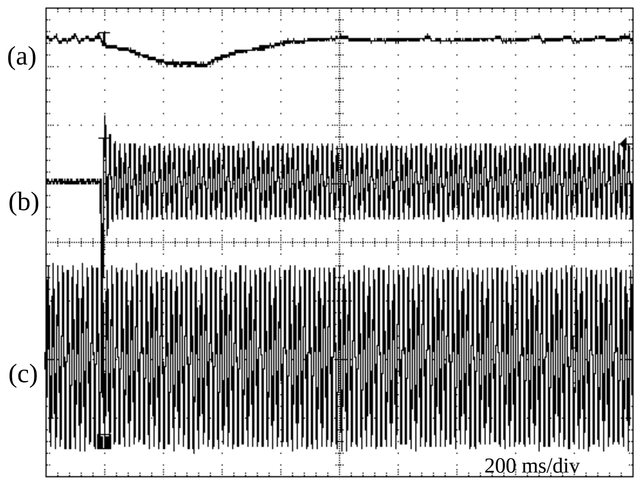

Fig. 11. a) V_{dc} Voltage (50 V/div.), b) AC load line current (2 A/div.) and c) IG terminal line voltage (200 V/div.) during load transient with regulated primer-mover.

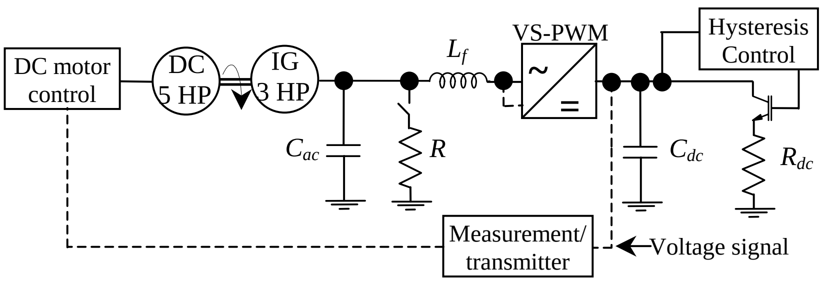

Fig. 9. The experimental arrangement

VI. CONCLUSION

An induction generator system driven by internal combustion engine with frequency and voltage regulation has been studied. Considering the advantages of IG compared with synchronous generators, the system is modeled to study the control strategy necessary to adjust the IC engine speed for compensating the load variation effects.

A DC motor emulates the IC engine behavior for experimental purposes. Simulated and experimental results confirm the expectations of getting a low-cost, high-quality energy source.

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