Experimental Setup for Autonomous Induction Generator System with Voltage and Frequency Regulation Studies

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Abstract: - A Diesel engine is commonly used to drive a generator for autonomous production of electricity. An induction generator associated with a PWM inverter can substitute the synchronous generator. The inverter allows stabilizing voltage and frequency, while the power flow is controlled adjusting the speed. This paper presents an investigation of a self-excited induction generator system with adjustable speed. The system uses a PWM inverter connected at the generator output and it is able to maintain constant three-phase voltage and frequency, eliminating the drawbacks of the induction generator isolated systems. For experimental purposes, a DC motor emulates the dynamic behavior of the Diesel motor. Considering the models and open-loop transfer functions of both motors, reduced-order dynamic representations and the necessary filters to match the models are obtained. Simulated and experimental results confirm that the system presents satisfactory behavior at steady state and under load transients. The experimental setup based on a DC motor can be used for laboratorial studies of the system.

Keywords: - Induction generator, Diesel engine modelling, production of electricity, DC motor, open-loop transfer functions, reduced-order model, model matching, filter circuits.

1 Introduction

A Generating Group (GG) is typically designed for autonomous production of electricity. These equipments present as main components the internal combustion (IC) engine (usually a Diesel engine, but the fuel could be a renewable fuel, as methanol or vegetal 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; that presents expensive costs of installation and operation due to fabrication and maintenance features.

It is frequently stated that squirrel-cage induction machines 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. Although IGs have such favorable features, in the past, they were hardly employed due to the unsatisfactory voltage regulation and frequency variation, even when driven under constant speed [1, 2].

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 has been 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 inverter [7, 8].

The proposed system is mainly composed of an IG excited by a three-phase capacitor bank (C_{ac}) and connected to the AC side of a 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.

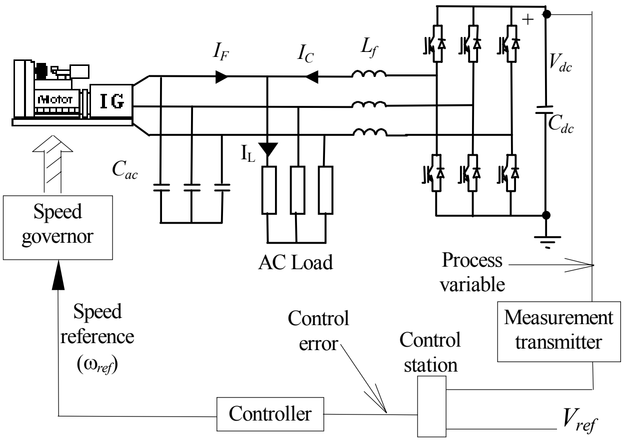

Fig. 1 IG based system configuration.

A good voltage regulation is obtained at the generator leads by maintaining constant the inverter DC voltage (V_{dc}). It is also possible to employ V_{dc} as a feedback signal to control a prime mover with speed governor [8], as shown in fig. 1.

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].

The speed control regulates the power balance and consequently the DC 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 any reactive power demand. The system also minimizes the current harmonics that circulates through the IG. Since both the inverter and the IG produce sinusoidal voltage, and they are coupled by passive impedance, the IG currents must be sinusoidal. In case of non-linear loads, the harmonics flow through the inverter

For experimental purposes, a DC motor emulates the dynamic behavior of the Diesel engine. The model-matching problem is traditional in control theory [9, 10]. Our goal is to design a system in which the controlled output of the DC motor (speed) matches, around a particular operating point, the output (speed) of the Diesel engine. Simulated and experimental results are shown to validate the proposed method.

2 Models

2.1 Diesel Engine and governor

Diesel motors are the most efficient internal combustion engines [11]. Smaller 4-stroke direct injection turbocharged motors can reach approximately 40% efficiency. 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 as a function of the load. It acts in the acceleration mechanism, supplying fuel without abrupt variations and responding softly to load variations.

The Diesel engine is a non-linear system. It 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 [12] to study the system response for fast speed perturbations, and a simpler model is enough [13].

A simplified general functional block diagram for a Diesel engine and the respective speed regulator system is presented in Fig. 2 [14, 15]. The model has three blocks: the speed governor, the fuel flow and the combustion process.

The speed governor determines the power (torque) output of the diesel engine. 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 fuel flow block is a gain that adjusts the relationship between the torque and fuel consumption.

The combustion block includes a time delay factor that represents the inertia of the engine in situations of acceleration and retardation. This dead time τ_1 is the result of having several cylinders. Not all cylinders will be in a position to accept more fuel at a given instant. It 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.

The effective 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 [16].

$$\tau_1 = \frac{60N_t}{2nN_c} + \frac{60}{4N_c} \tag{1}$$

Where N_t = 2 or 4 for two or four-stroke engine; N_c= number of cylinders and n = speed in rev/min.

Considering $N_t = 4$, $N_c = 4$ e $n \approx 1800$ rpm ($\tau_1 = 25$ ms) and the other appropriate parameters of a Diesel engine [13], the transfer functions of the system shown in fig. 2 yields

$$F_{Di1}(s) = \frac{\omega(s)}{T_L(s)} = \frac{-10}{s + 0.21} \tag{2}$$

$$F_{Di2}(s) = \frac{\omega(s)}{C(s)} = \frac{1}{(1 + 0.075s)(0.021 + 0.1s)} e^{-0.025s} \tag{3}$$

It can be shown by suitable eigenvalue techniques, that the behavior of a plant with input time-delay can be approximate by appropriate rational function.

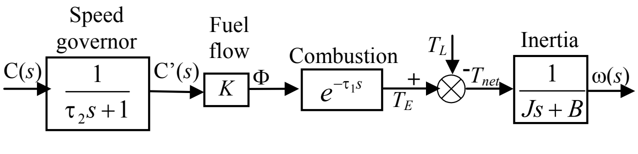

Fig. 2 Diesel engine - governor model.

Using Padé approach of second order [17] in (3), the open-loop transfer function ω(*s*)/*C*(*s*) becomes

$$F_{Da}(s)=\frac{133.3s^2-3.2\cdot 10^4 s+2.56\cdot 10^6}{s^4+253.5s^3+2.2\cdot 10^4 s^2-2.6\cdot 10^5 s+5.4\cdot 10^4} \tag{4}$$

2.1 DC Motor

The basic block diagram of a DC motor fed by a converter, with independent and constant excitation, is shown in fig. 3. For R_a = 2.0 Ω, L_a = 11.5 mH, K_E = 1.15 V/rad/s, K_T = 1.11 N.m/A, K_2 = 23.5, J=0.071 Kg.m^2 and B = 0.0062 N.m/rad/s, taking as inputs $V_r(s)$ and $T_L(s)$, and as output ω(*s*), the transfer functions are

$$F_{CC1}(s)=\frac{\omega(s)}{T_L(s)}=\frac{-14.08s-2449.5}{s^2+174s+1578.6} \tag{5}$$

$$F_{CC2}(s)=\frac{\omega(s)}{V_r(s)}=\frac{31947}{s^2+174s+1578.6} \tag{6}$$

3. Filter for Load Disturbance

The Diesel engine and the DC motor transfer functions $\omega(s)/T_L(s)$ are given by equations (2) e (5) respectively. The correspondent ω(*s*) responses for a $T_L(s)$ step are shown in Fig. 4.

The objective is to emulate the dynamic behavior of a Diesel engine using a DC motor based system, adding the necessary filter. The problem can be substantially simplified by using traditional model reduction order techniques. It can be shown that the dynamic behavior of armature inductance L_a can be neglected (Fig 5) and considering the DC motor is non-saturated (5) yields:

$$F_{CC1r}(s)=\frac{-14.0845}{s+9.077} \tag{7}$$

It is necessary to compensate the natural speed feedback of the DC motor, and then to balance the delay constant (mechanic) of the DC motor with regard to the diesel engine. It can be determined including a factor *S(s) = a.s + b* in series with feedback branch of the DC motor model, as shown in fig.6.

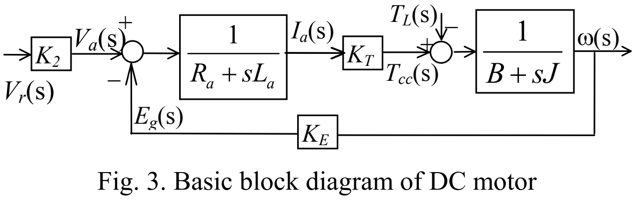

Fig. 3. Basic block diagram of DC motor

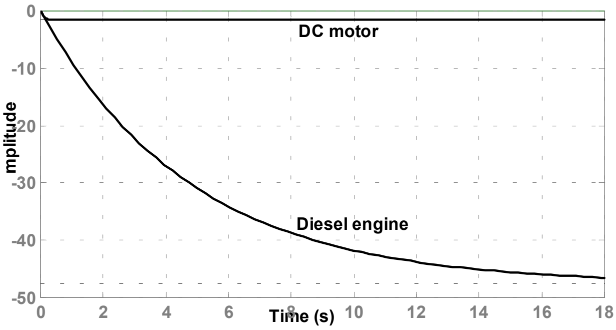

Fig. 4 Load step responses of DC motor and Diesel engine.

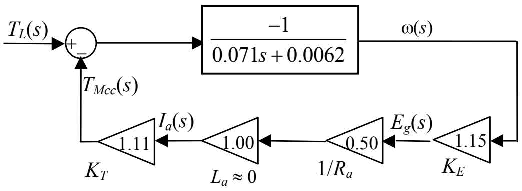

Fig. 5 Block diagram for ω*(s)*/$T_L(s)$ of DC motor, for L_a=0.

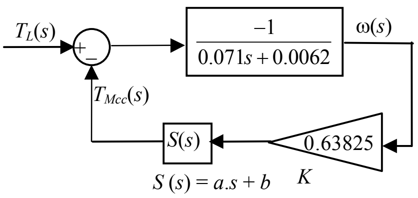

Fig. 6. Inclusion of *S*(*s*).

In this manner

$$\frac{\omega(s)}{T_L(s)}=\frac{\dfrac{-1}{\cancel{0.071s+0.0062}}}{\dfrac{0.071s+0.0062+0.63825\cdot S(s)}{\cancel{0.071s+0.0062}}}\cong\frac{-1}{0.1s+0.021}$$

$$S(s)=0.0454s+0.0232 \tag{8}$$

As it is impossible to open the inner speed feedback of a DC motor, a suitable realization arrangement is to get the $I_a(s)$ value, which is straight proportional to $T_{CC}(s)$, and execute a feedback circuit that compensate any variation in $E_g(s)$, as shown in Fig. 7. The transfer function *R*(*s*) in the feedback branch that produces an equivalent effect to factor *S*(*s*) is

$$R(s)=\frac{-0.0454s+0.9768}{0.0454s+0.0232} \tag{9}$$

Fig. 8 shows the inclusion of *R*(*s*) and K_3 in the block diagram of the DC motor. The K_3 gain adjusts the relation between the output of *R*(s) and the $V_r(s)$ reference voltage.

Fig. 9 presents the speed response to a load step of the Diesel engine, the same is done for the DC motor emulating a Diesel engine. Observe that the designed filter was effective in the model matching.

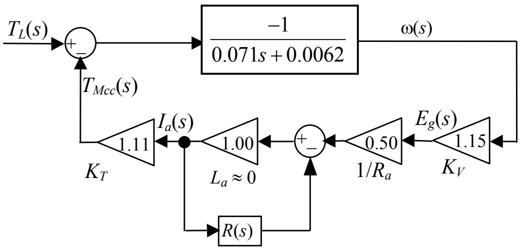

Fig. 7. Inclusion of $R(s)$.

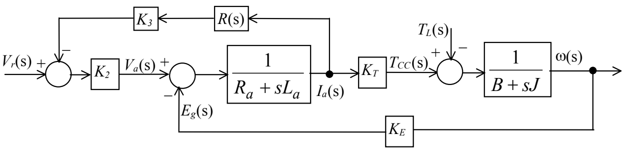

Fig. 8. Block diagram of DC motor+ R (s)

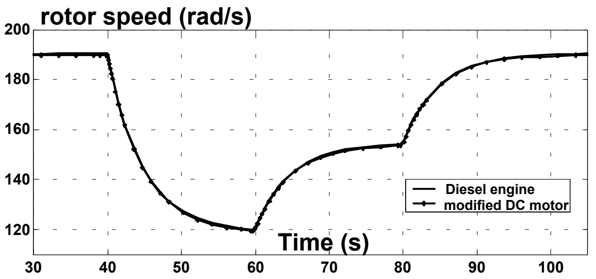

Fig. 9 Modified DC motor and Diesel engine responses: comparison of load step variation at t = 40, 60 e 80 s.

4 Filter for Input Voltage Disturbance

The transfer function $\omega(s)/V_r(s)$ of the DC motor fed by a converter, and including $R(s)$ is given by

$$F_{CC21}(s) = \frac{51116s + 26121}{s^3 + 87.6s^2 + 2749s + 570.6} \qquad (10)$$

The fig. 10 shows the Bode diagrams corresponding to the Diesel engine (DE), its modified model according to eq. (4) (DER), and the DC motor including the current feedback according to eq. 10 (DCM).

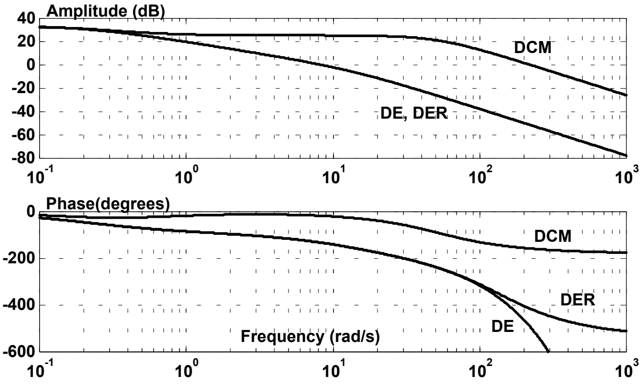

Fig. 10. Bode diagram: Diesel engine, Diesel engine with rational approximation and DC motor including *Ia* feedback

The model matching problem can be formulated for systems represented by transfer functions of the following form [9]: Let $\mathbf{RH}_\infty$ be the set of real, rational, stable and proper transfer functions. Taking two functions $T_1(s)$, $T_2(s) \in \mathbf{RH}_\infty$ determine $Q(s) \in \mathbf{RH}_\infty$ such that the *infinity norm*

$$\left\| T_1(s) - T_2(s)\cdot Q(s) \right\|_\infty \qquad (11)$$

be minimal. Let $T_1(s) = F_{Da}(s)$ and $T_2(s) = F_{CC21}(s)$ be the known transfer functions.

In this case, the problem is analytically solved by doing $Q(s) = F_{Da}(s)/F_{CC21}(s)$. $Q(s) \in \mathbf{RH}_\infty$, that has five states. Utilizing a technique for model order reduction, two states can be eliminated without affecting considerably the frequency response. $Q(s)$, takes the following form

$$Q_{red2}(s) = \frac{0.002608s^3 - 0.5413s^2 + 29.73s + 1200}{s^3 + 215.2s^2 + 2347s + 1153} \qquad (12)$$

Fig. 11 shows the inclusion of $Q(s)$ in the block diagram of the DC motor. Fig. 12 presents the Bode diagram of the Diesel engine model, the Diesel engine model with rational approximation and DC motor model including $R(s)$ and $Q(s)$ - MDC*. A comparison between the two time responses (fig. 13) shows that they are very similar for $V_r(s)$ and $T_L(s)$ steps.

5 Experimental Results

Considering the models and open-loop transfer functions of both motors, a reduced-order dynamic representation and the necessary filters to match the models were obtained and implemented by analogical circuits.

Fig. 14 shows the speed and armature current variations when the motor is submitted to a load step. When the DC motor emulates the dynamic behavior of the Diesel engine, the speed reduction is much heavier, as anticipated in Fig. 4.

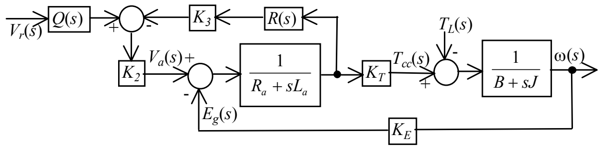

Fig.11 DC motor block diagram with $R(s)$ and $Q(s)$ – DCM*

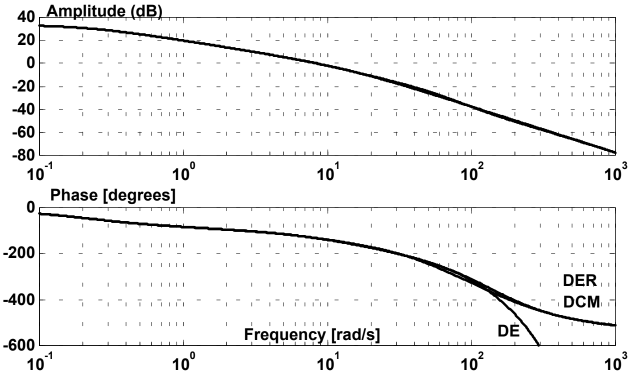

Fig. 12. Bode diagram: diesel engine (DE), diesel engine with rational approximation (DER) and DC motor including $R(s)$ and $Q(s)$ (DCM).

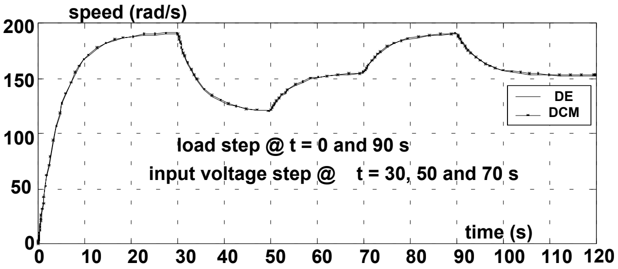

Fig.13. Comparison between the two time responses

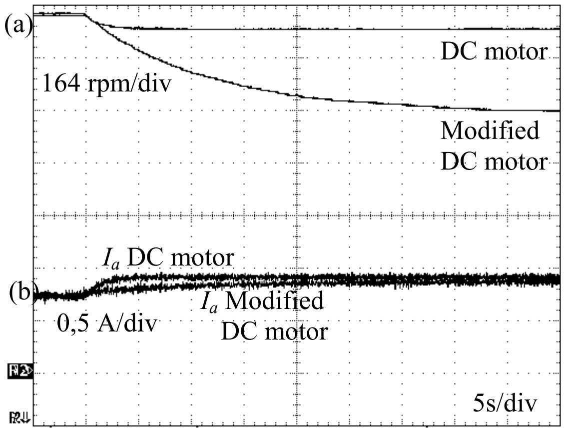

Fig. 14 Experimental results for DC motor emulating the dynamic behavior of the DE: (a) Rotor speeds, and (b) armature currents (I_a) to a same load torque step.

An IG system, as shown in fig. 1, with the proposed control strategy was implemented. The preliminary experimental results still use the non modified DC motor as prime mover.

The induction machine used as generator has the following nominal characteristics as motor: 3 HP, 220 V, 60 Hz, 4 poles, delta connection. The IG is connected to a commercial PWM inverter that was set up to produce 60 Hz and 220V.

The IG startup was obtained though by the self-excitation due to the interaction between the residual rotor flux and C_{ac}. Since the prime mover is not able to produce negative torque to breaking the rotor, for security purposes a chopper with resistive load 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. 15 shows a load transient without speed correction. Part of the energy stored in C_{dc} is employed to the power balance, resulting in an AC voltage reduction due to the DC link voltage variation.

Fig. 16 shows a load transient with regulated prime mover. The voltage sag is eliminated due to the speed controller action (V_{dc} Control).

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.

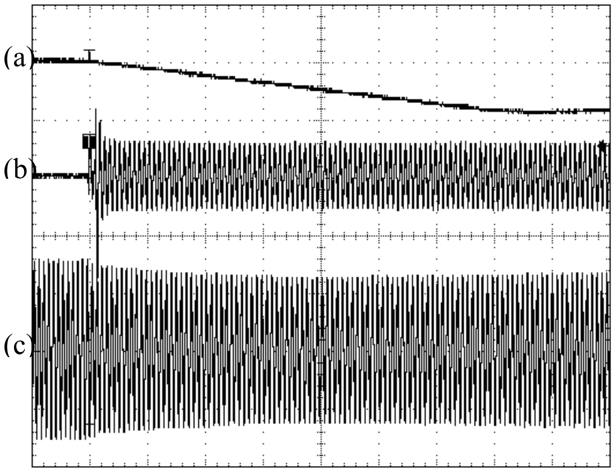

Fig. 15 a) V_{dc} Voltage (50 V/div.), b) AC load line current (2A/div.) and c) IG terminal line voltage (200V/div.) during load transient without speed correction. Horiz:. 200 ms/div.

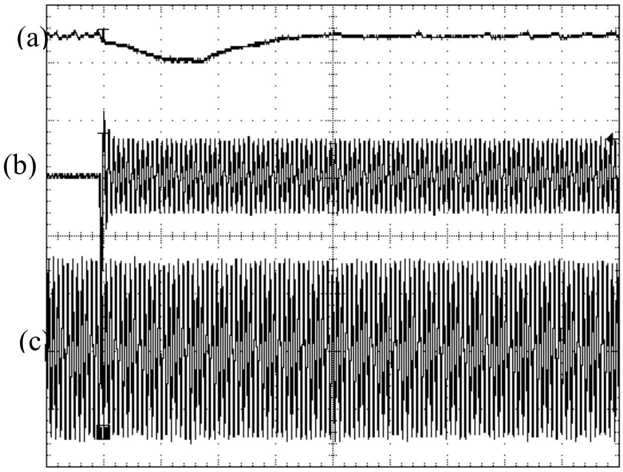

Fig. 16 a) V_{dc} Voltage (50 V/div.), b) AC load line current (2A/div.) and c) IG terminal voltage (200V/div.) during load transient with regulated primer-mover. Horiz.: 200 ms/div.

6. Conclusion

A DC motor system was developed in order to dynamically emulate the IC engine behavior for experimental purposes. Filters were developed to be added to a DC motor driver such that, the system emulates the dynamic behavior of the Diesel engine

Simulated and experimental results confirm that the experimental setup based on the DC motor can be used for laboratorial studies of the system.

Considering the advantages of na IG compared with synchronous generators, this system allows to study the control strategy to adjust the IC engine speed for compensating the load variation effects.

The PWM inverter DC voltage control (V_{dc} control), exerted by the speed governor, indicates that it is an effective, fast, and reliable technique to obtain power balance, and to regulate the amplitude of the terminal voltage.

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