DYNAMIC MODELING AND CONTROL OF AN ICE-DRIVEN INDUCTION GENERATOR WITH VOLTAGE AND FREQUENCY REGULATION BY PWM THREE-PHASE INVERTER

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Abstract **– This paper presents the use of self-excited induction generator with controlled speed associated with a PWM inverter. The inverter allows stabilizing voltage and frequency, while the power flow is controlled adjusting the speed. It is discussed the use of induction generator as an alternative to synchronous generators in low power, internal combustion engine driven systems. The power limit for this approach is related with the PWM inverter capacity and also to the dynamic system response that determines the design of some critical components, as the DC capacitor. For experimental purposes, in laboratory, it is made the emulation of the dynamic behavior of a diesel engine through a DC motor driving system. The experimental system allows the development of project methodologies for induction generator based system. The obtaining of regulated voltage with constant frequency is verified in a prototype of 3 HP.**

KEYWORDS

Induction generator, inverter, filter circuits, dynamic behavior, diesel engine, PID controller.

I. INTRODUCTION

Generating Groups (GG) are designed for autonomous production of electricity. These equipments present as main components the internal combustion engine (ICE), usually a diesel engine, the generator, and the control unit.

They are used in situations like places without electricity supply; 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 easy maintenance and operation.

Diesel engine is the most efficient ICE [1]. Smaller 4-stroke direct injection turbocharged diesels 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 note that the technically realizable diesel cycle does not differ substantially from the thermodynamically ideal one.

Usually the generator is a synchronous machine, which 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. Nevertheless, 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 known 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. Despite these features, in the past, IMs were hardly employed as generators due to its unsatisfactory and frequency variation, even when driven under constant speed and feeding active power loads [2, 3].

The advancement of power electronics and drives technology brought new perspectives to improve the voltage regulation [4, 5]. Recent studies explore the use of standard PWM inverters to obtain a reasonably stable voltage operation with a simple structure [6, 7].

The goal of this article is to verify the behavior of an IG as an alternative to synchronous generators in low power, fuel engine driven systems. For experimental purposes, in laboratory, it is made the emulation of the dynamic behavior of a diesel engine through a DC motor driving system. Simulated results employing a PID controller are reported. Experimental results obtained from a 3 HP system are shown to validate the proposed method.

II. SYSTEM CONFIGURATION

The system, shown in Fig. 1, 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 voltage components. A speed governor controls the IG rotor shaft speed. The main objective of this structure is to feed the AC load with satisfactory power quality: three-phase balanced voltages, with constant frequency, sinusoidal waveform and regulated amplitude.

The prime mover is an ICE; the speed regulator is the injection fuel system, which is a component of the motor. Thus, the speed reference (ω_{ref}) signal is proportional to the amount of fuel to be injected into the motor, as an electronic accelerator [7].

The fundamental frequency of the PWM inverter output voltage is maintained constant at 60Hz, yielding a constant frequency at the load leads. At the DC side of the inverter

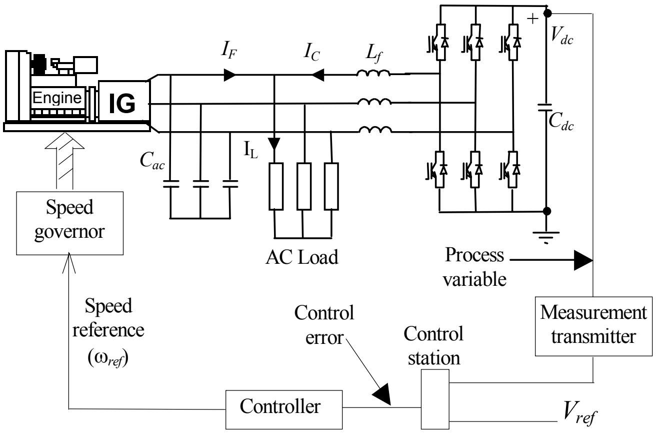

Fig. 1 – IG based system configuration.

there is not a power source, but only a capacitor. In case of power deficit (consumed power is greater than the generated power), the energy stored in C_{dc} supplies the load, reducing the 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 inverter, the generated power is proportional to the rotor slip, thus it depends on the ICE 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 voltage.

III. SYSTEM MODELING

The rotation speed of a diesel engine 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 engines 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 in a soft mode to load variations.

A simplified general functional block diagram for a diesel engine and the respective speed regulator system is shown in Fig. 2 [8, 9]. 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. K_3 is a gain that adjusts the control signal in order to drive the actuator. The typical set of per unit used in simulation studies is shown in [10].

For experimental purposes, a DC motor emulates the dynamic behavior of the Diesel engine. The model-matching problem is traditional in control theory [11]. 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. Fig. 3 presents the speed responses of a Diesel engine and a DC motor for a step in the torque input.

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.

Fig. 4 presents the speed response to a load step of the standard DC motor drive systems, and when emulating a Diesel engine. Observe that the designed filters were effective in the model matching.

Both standard and controlled DC motor drive systems were implemented. Fig. 5 shows the speed and armature current when both systems were submitted the same load step. When the DC motor emulates the dynamic behavior of the Diesel engine, the speed reduction is much heavier, as anticipated in Fig. 3.

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 AC loads, the system losses and the control circuits, as well as to keep C_{dc} properly charged. Consequently, the speed reference ω_{ref} is variable and is proportional to the load power.

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, 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.

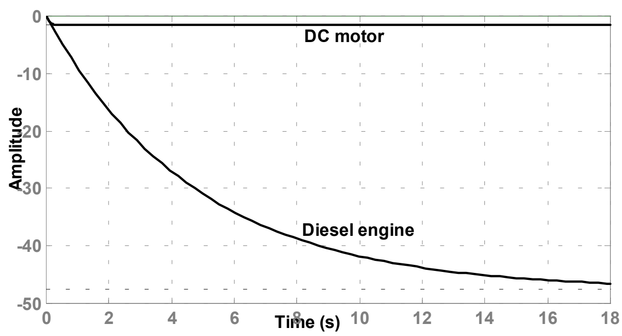

Fig. 3 – Load step responses of DC motor and Diesel engine.

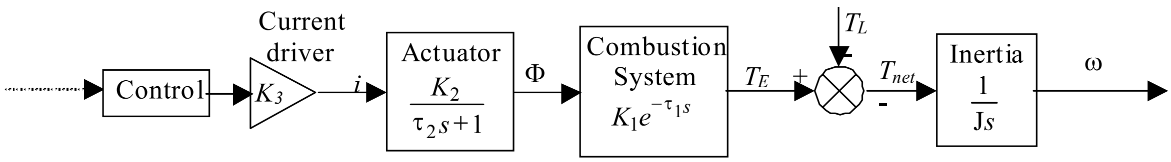

Fig. 2 – Diesel engine - governor model.

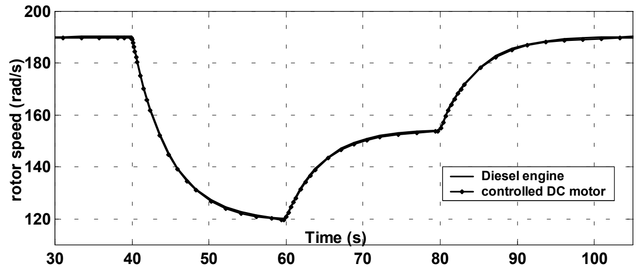

Fig. 4 – Modified DC motor and Diesel engine responses: comparison of load step variation at t = 40, 60 e 80 s.

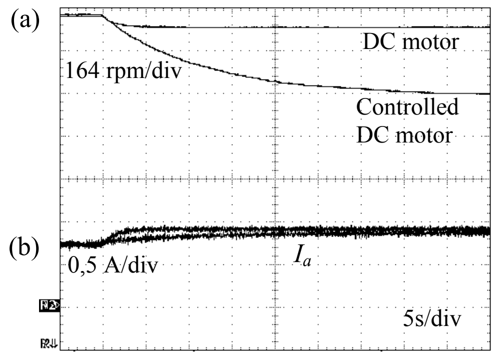

Fig. 5 – Experimental results for DC motor emulating the dynamic behavior of the Diesel engine: (a) Rotor speeds, and (b) armature currents (I_a).

Neglecting the losses, power balance occurs when the generated power (P_g) is equal to the power drawn by the load (P_L). During transients, the capacitor C_{dc} provides to energy to the load or stores energy, minimizing the variations in V_{dc}.

The stored energy variation in the capacitor is:

$$\Delta\varepsilon = \int \Delta P dt = \int \left(P_g - P_L\right) dt \tag{1}$$

The total capacitor stored energy variation is:

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

where V_f and V_i are respectively the final and the initial DC voltage associated with a load transient.

Thus, the variation of the capacitor voltage is:

$$\Delta V = \frac{\Delta\varepsilon}{C_{dc}\cdot\overline{V}} \tag{3}$$

IV. SIMULATION RESULTS

The setup used in SIMULINK simulation is shown in Fig. 6. The induction machine is modeled using the arbitrary reference-frame d-q axis equivalent circuit for a thee-phase, symmetrical machine [10].

The DC voltage, that indicates the power balance, is compared with the reference and the error is applied to a PID regulator, designed according the Ziegler-Nichols method [12, 13]. The system response to load variations was analyzed in order to determine the DC capacitance necessary to maintain the DC voltage within an acceptable range.

Fig. 7 shows the DC voltage variation for different load steps. In fact the AC voltage variation is lower due to the IG influence on the load bus.

Fig. 8 displays a full load transient, with the same PID parameter values. As expected, as the load increases, the motor must accelerate to augment the generated power. The capacitance value depends on the maximum load power and on the system response to transients. The minimum value is obtained for the fastest response, which minimizes the power deficit during load connection.

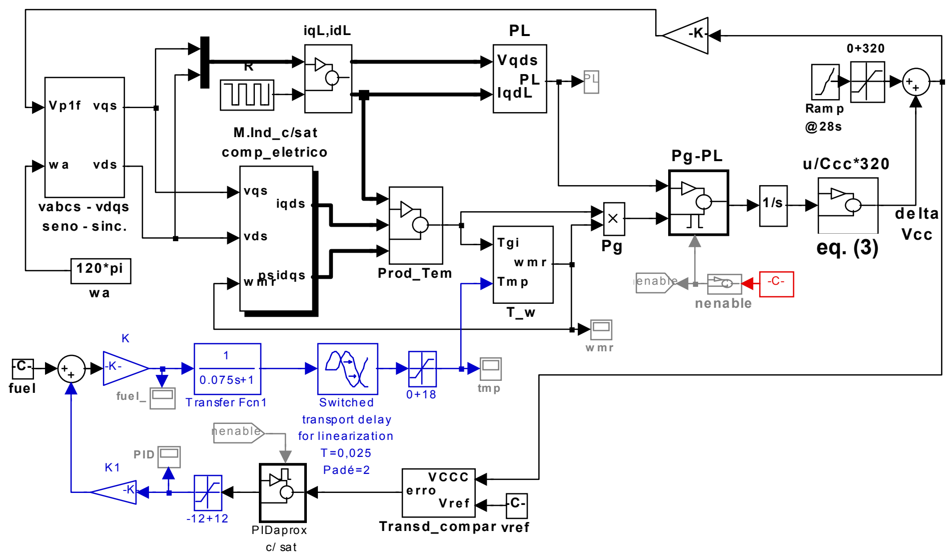

Fig. 6 – Induction generator system driven by an Internal Combustion Engine.

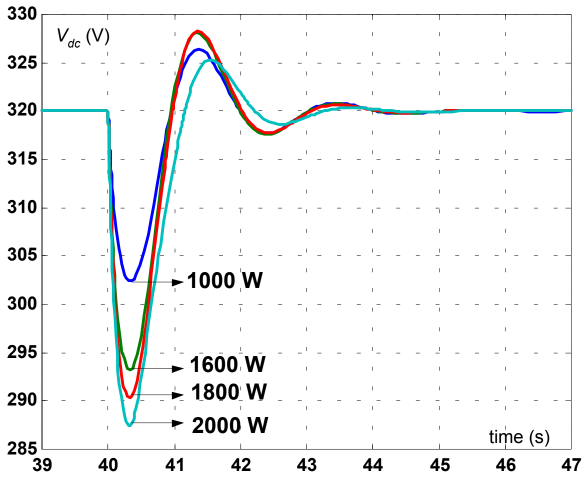

Fig. 7 – DC voltage variation for different load steps (C_{cc} = 42 mF), with PID regulator (K_p = 25; K_i = 40; K_d = 2.5; T_n = 100).

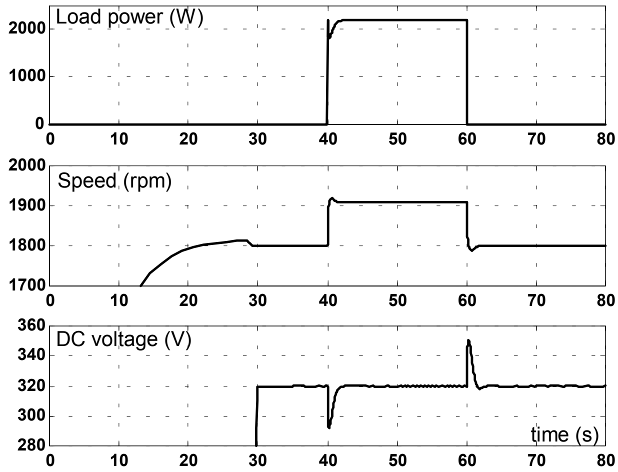

Fig. 8 – Full load transients.

V. EXPERIMENTAL RESULTS

Fig. 9 shows the laboratory experimental setup. A DC motor driven by a power converter was used to emulate the ICE. $Q(s)$ and $R(s)$ filters were designed in order to fit the DC motor system dynamic response with a typical ICE behavior [14, 15].

Since the prime mover isn't able to produce a negative torque to braking the rotor, a DC-link resistance (with hysteresis control) was utilized to avoid over-voltages during AC-load disconnection. If the DC voltage becomes higher than a threshold an IGBT connects the DC resistence in order to absorb the power.

The IG is a 3 HP, 220 V, 60 Hz, 4 poles, delta connection motor. The IM parameters are shown in [10]. The PWM inverter commutates at 2 kHz. Other components are: C_{ac} = 36.5 μF (Y); C_{dc} = 10 mF and L_f = 10 mH.

The PID regulator parameters were calculated using the Ziegler-Nichols first method. For such C_{dc} value, the system should present less than 10% voltage variation for a 500W load step, as shown in Fig. 10. Notice that there is no over-voltage due to the limiter action, what changes the waveform respect to the simulation result.

Fig. 11 shows the response for a 1 kW load step, which, for the same PID parameters, presents a 90 V voltage sag. For this situation, in order to limit the voltage sag it would be necessary to increase the DC capacitance value. Fig. 12 shows the AC voltage variation is lower than the DC voltage variation due to the IG influence on the load bus. The 90V sag at the DC bus corresponds to 40V reduction at the AC bus.

Fig. 13 shows that the AC bus frequency remains constant even during a load step because the frequency is imposed by the inverter.

The voltage waveform is practically sinusoidal, with a total harmonic distortion (THD) of 2%. Partially the distortion is due to non-idealities of the induction generator.

Also for a non-linear load step (Fig. 14) no frequency variation is observed, but the voltage suffers a small distortion because the harmonic components of the load current are distributed among the IG, inverter and AC capacitor, according the respective reactance. The THD is about 3.5%.

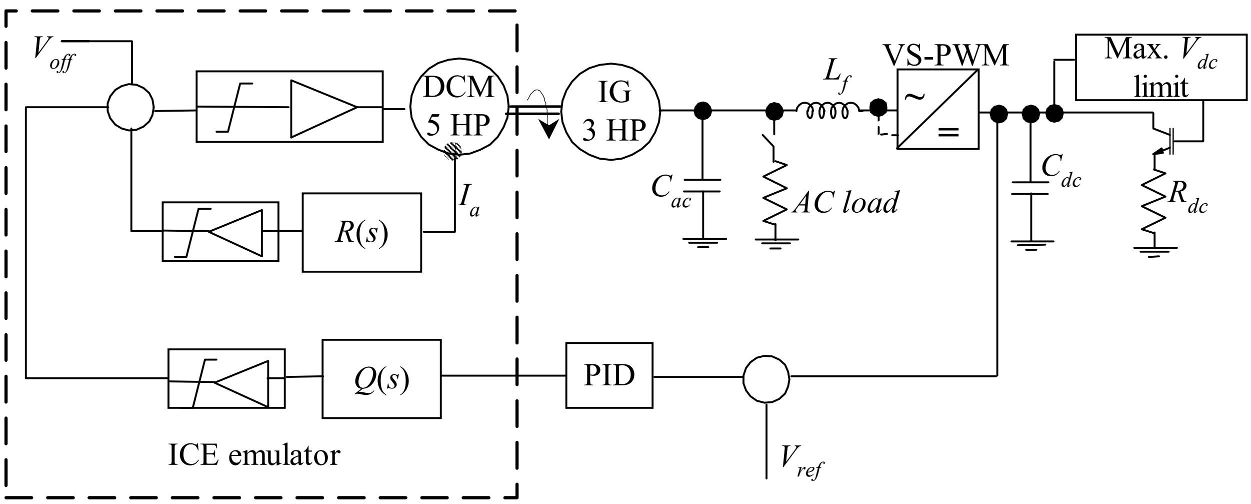

Fig. 9 – Experimental setup with primary mover, induction generator, PWM inverter, variable load and control circuits.

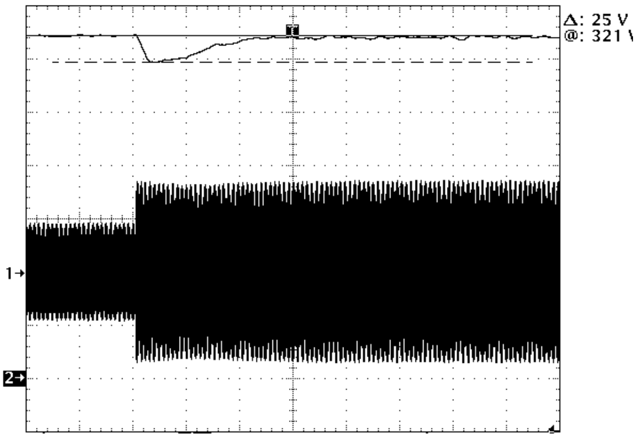

Fig. 10 – Load transient response (500 W → 1 kW): (1) AC bus current (2 A/div), (2) V_{dc} (50 V/div). Time: 1 s/div. $K_p = 5.28$; $K_i = 5.28$; $K_d = 1.32$.

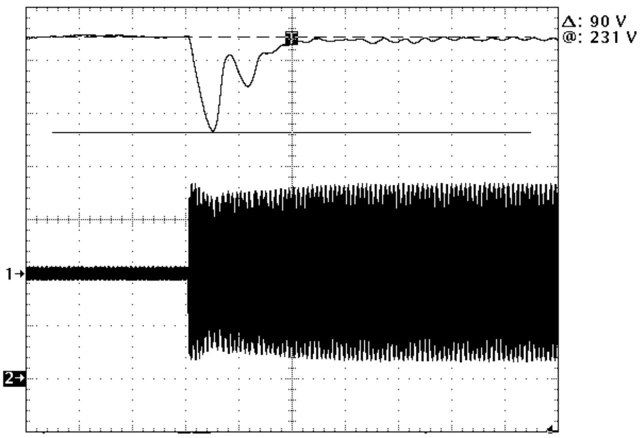

Fig. 11 – Load transient response (1000 W): (1) AC bus current (2 A/div.), (2) V_{dc} (50 V/div.). Time: 1 s/div. $K_p = 5.28$; $K_i = 5.28$; $K_d = 1.32$.

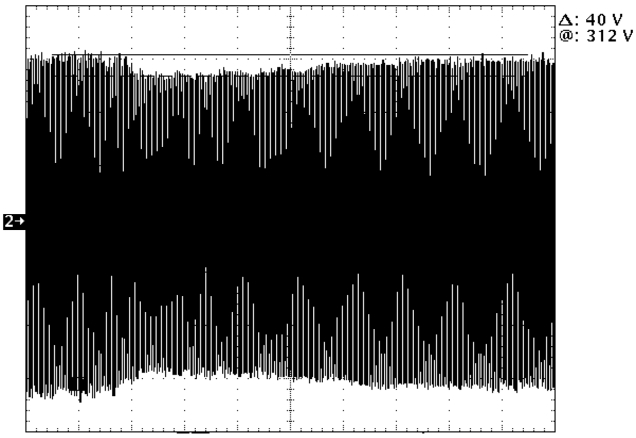

Fig. 12 – AC voltage variation for 1000 W load step. Voltage: 50 V/div. Time: 1 s/div. $K_p = 5.28$; $K_i = 5.28$; $K_d = 1.32$.

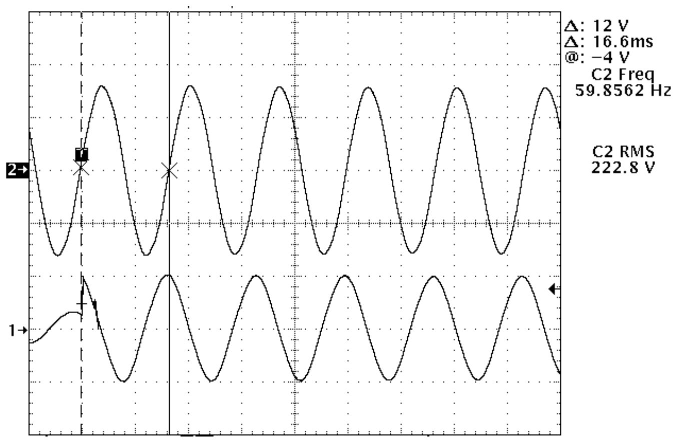

Fig. 13 – Load transient response (50 W →200 W): (1) AC bus current (1 A/div.), (2) AC voltage (200 V/div.). Time: 10 ms/div.

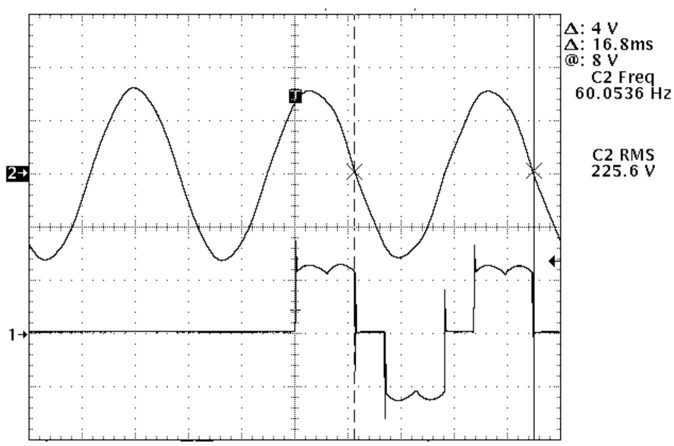

Fig. 14 – Non-linear load transient (400W): (1) AC bus current (1 A/div.), (2) AC voltage (200 V/div.). Time: 5 ms/div.

VI. CONCLUSION

The use of a PWM inverter together with an induction generator is an interesting alternative to obtain stable voltage and frequency, and could substitute conventional synchronous machines in generators groups driven by internal combustion engines. The inverter naturally compensates the reactive power of the load because it maintains the AC voltage level and frequency. In the event of load transients, the DC link capacitor delivers or absorbs the power difference. To minimize the capacitance value, it is necessary to have the fastest ICE response in order to establish the power balance. For some kWs it is possible to use electrolytic capacitors. For higher power, another kind of energy storing should be used, as a battery bank (that could works like an UPS system) or a supercapacitor [16].

The simulation results, based on the ICE typical parameters are consistent with the experimental results that were obtained with a modified DC motor driven system that presents the same ICE dynamic response.

VII. ACKNOWLEDGMENT

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