IMPLEMENTATION OF A MICROCOMPUTER BASED START-UP AND SPEED CONTROL SYSTEM FOR A SYNCHRONOUS MACHINE DRIVE

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Abstract **– This paper shows an implementation of a controlled synchronous machine drive, using thyristor current inverter with digital firing circuit. The firing angle of the inverter bridge is maintained constant in 150 degrees, while the speed and current control of the machine is obtained by changing the rectifier unit firing angle. The arrangement is similar to the control of a DC machine with two PI (proportional – integral) regulators of speed and current in cascade, controlling the firing angle of the rectifier unit. Th e optimization of the regulators using the symmetric optimization criterion, as well as the machine starting method and speed regulation procedure are shown in the paper, and the obtained experimental results presented and discussed.**

Keywords **– Synchronous Machines, PID regulators, Current Source Inverter, Synchronous Machine Electronic Starting Method.**

I. INTRODUCTION

The evolution of power electronics and control techniques has allowed a more extensive use of synchronous motors instead of drives which use dc machines. The control of synchronous machines through current injection allows the synchronous motor to be considered a commuter-less dc motor. That is because the commuter makes the use of dc motors impossible in environments with risk of explosion, or with large amount of dust, or other particles in suspension, besides having an easier maintenance.

II. DRIVE OF THE SYNCHRONOUS MACHINE

The drive for the synchronous machine is made up by a rectifier bridge and a six-pulse inverter bridge using thyristors, as shown in figure 1.

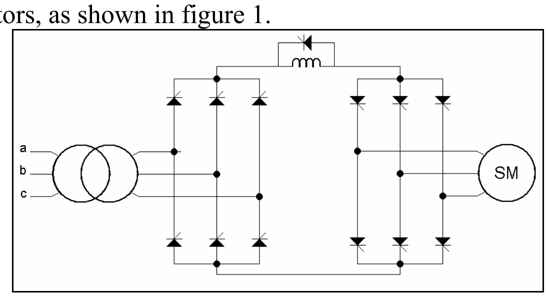

Fig. 1. Synchronous Machine Drive

The rectifier bridge is responsible for converting the network three-phase voltage into a DC voltage. This continuous voltage is converted by the inverter into six current pulses of square wave. Such pulses are applied to the machine terminals making it to operate. The machine speed is related to the voltage value in the rectifier unit, which is achieved by changing the rectifier bridge firing angle. Such angle is dynamically defined by a closed grid control.

III. SYNCHRONOUS MACHINE CONTROL

The mechanical model and electrical circuit are shown in figure 2.

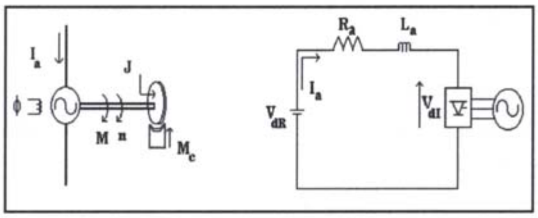

Fig. 2. Representation of the mechanical section and the electrical circuit of the synchronous motor.

Where:

V_{dR}: Rectifier output dc voltage
V_{dI}: Inverter output dc voltage
L_a: Total inductance
R_a: Total resistance
ϕ: Motor flow
I_a: Armature current
M: Motor torque
m: Motor torque p.u. (M/ M_n)
M_c: Load or resistant torque
m_c: Load or resistant torque p.u. (M_c/ M_n)
B: Accelerating torque ($B=M-M_c$)
b: Accelerating torque p.u. (B/M_n)
J: Inertia momentum (motor+load)
n: Speed (RPM)
ω: Rotation (Rad/s)

Equationing:

$$M = K.\ \phi.\ I_a \tag{1}$$

$$B = J.\frac{d\omega}{dt} \tag{2}$$

$$\omega = \frac{2.\pi}{60}.n \quad (3)$$

By substituting equations (1) and (3) in (2):

$$n = \frac{n_N}{M_n}.\frac{M_n}{J.\frac{2.\pi}{60}.n_N}.\int B.dt \quad (4)$$

$$T_H = \frac{2.\pi}{60}.\frac{J.n_N}{M_n} \quad (5)$$

This is the time constant that represents the time necessary the motor takes to reach rated speed, starting from rest. This motor is accelerated through a resulting torque equal to the motor rated torque. Figure 3 shows.

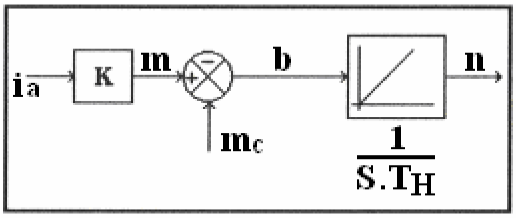

Fig. 3. Block diagram of the synchronous machine mechanical part.

For the armature circuit:

$$V_{dR} = R_a I_a + L_a \frac{dI_a}{dt} + V_{dI} \quad (6)$$

By applying the Laplace transform into equation (6)

$$V_{dR}(s) = R_a I_a(s) + SL_a I_a(s) + V_{dI}(s)$$
$$V_{dR}(s) - V_{dI}(s) = I_a(s)[R_a + SL_a]$$
$$I_a(s) = \frac{V_{dR}(s) - V_{dI}(s)}{R_a + SL_a} \quad (7)$$

If we define $T_a = \frac{L_a}{R_a}$

$$I_a(s) = \frac{V_{dR}(s) - V_{dI}(s)}{1 + ST_a}.\frac{1}{R_a}$$
$$\frac{I_a}{I_N} = \frac{V_{dR} - V_{dI}}{V_N} \times \frac{V_N}{R_a.I_N} \times \frac{1}{1 + ST_a} \quad (8)$$

obtaining the values of the armature current and of voltages V_{dR} and V_{dI} in pu:

$$i_a = \frac{I_a}{I_N} \text{ (pu)}$$

$$v_{dR} = \frac{V_{dR}}{V_N} \text{ (pu)}$$

$$v_{dI} = \frac{V_{dI}}{V_N} \text{ (pu)}$$

By making $v_i = \frac{V_N}{R_a I_N}$, the following figure 4 block diagram results:

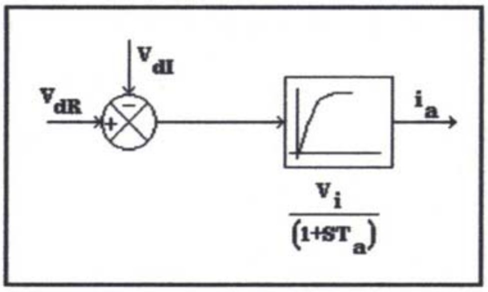

Fig. 4. Equivalent block diagram of the synchronous machine armature circuit.

By taking:

$$i_a = (v_{dR} - v_{dI}).\frac{v_i}{1 + ST_a} \quad (9)$$

Where:

V_N: rated V_{dR}
I_N: rated I_a
I_a: Current in the dc link

By substituting:

$$V_{dR} = E \quad (10)$$

$$V_N = E_N \quad (11)$$

$$E = 1.35.U_2.\cos(\alpha) \quad (12)$$

$$\frac{d_E}{d\alpha} = -1{,}35.U_2.\mathrm{sen}(\alpha) \quad (13)$$

Where:

U_2: RMS Supply voltage of the rectifier (line-line) (V)
α: Rectifier firing angle
α_u: Firing angle in “pu”

$$\frac{d(E/E_N)}{d(\alpha/\pi)} = -1{,}35.\frac{U_2}{E_N}.\pi.\text{sen}(\alpha) \quad (14)$$

In pu:

$$\frac{d(e)}{d(\alpha_u)} = -1{,}35.\frac{200}{187}.\pi.\text{sen}(\alpha) \quad (15)$$

Note: The U_2 and E_N values were measured in laboratory.

By defining the converter static gain as: maximum α=90º and minimum α=46º:

$$V_{S1} = \left|\frac{de}{d\alpha_u}\right|_{\alpha=90^o} = 4.53 \quad (16)$$

$$V_{S2} = \left|\frac{de}{d\alpha_u}\right|_{\alpha=46^o} = 3.26 \quad (17)$$

$$V_S = 3.90 \text{ (medium)} \quad (18)$$

The constant v_i can be interpreted as the multiplier factor of the rated current to obtain the current with locked rotor.

The factor $\frac{v_i}{1+ST_a}$ can be considered as a first order retarding element.

The determination of the time constant T_a can be made by measuring the inductance L_a and the resistance R_a of the armature circuit.

$$T_a = \frac{L_a}{R_a} \quad (19)$$

Results the following diagram of figure 5.

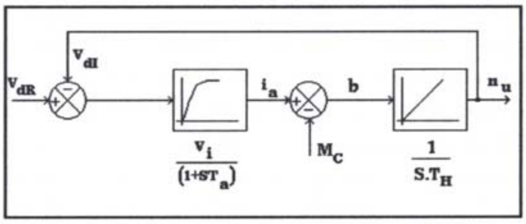

Fig. 5. Full block diagram of the machine in pu.

The optimization of the control grid is based on the relationship among the several time constants that appear in the system, so as to determine the most suitable controller characteristics. For a system that does not present any integral action element, the method in function of the module (OM) is indicated, which is derived from the accommodation of the frequency response module in the unit value for the largest margin of frequencies possible. This way, the fast effect correction of a reference step is allowed so as to guarantee a performance with dampening relationship of ξ = 0.707 and *overshoot* of M_0 = 4% approximately, without presenting significant oscillations. However, the correction of a disturbance effect is slow.

The optimization method in function of symmetry (OS) is indicated for systems that present retarding elements, proportional action elements, and integral action elements. Its main advantage is the fast effect correction due to disturbances. However, they can present an overshoot as high as 43% in the degree response. The introduction of a smoothing component in the reference signal reduces the overshoot but increases the accommodation time of the system degree response.

The optimization in function of the linearity (OL) only has sense in cases in which the overshoot must be null, although with very slow response, and in that the effect correction of disturbances is of secondary importance.

The armature current control grid of the synchronous machine is formed by a current regulator that drives the trigger circuit of the thyristor static converter that, as mentioned, controls the current level of the dc link and, as a consequence, the synchronous machine torque. The current signal of the synchronous machine is feedback into the system through a current transformer and a diode rectifier bridge in the outlet, giving rise to the necessity of a filter to feedback the circuit. In addition, a filter for smoothing of the reference signal of the current control grid is used, canceling the zero inserted by the current regulator. Figure 6 shows the current regulation loop.

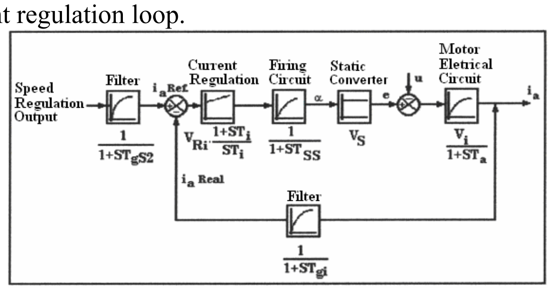

Fig. 6. Current regulation loop.

The formation of the speed control grid is completed by a speed governor, for which the current control grid is presented as a first order system with equivalent time constant T_e, feedback by a tachogenerator (standard 0-10V). There are two other filters, one for oscillations of the voltage signal of the tachogenerator and another for the zero inserted by the speed governor. (In order to decrease the overshoot response of the sped regulation loop). Figure 7 shows.

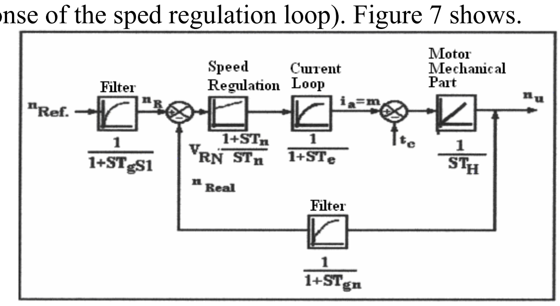

Fig. 7. Speed regulating grid.

The time constants of the control grid are experimentally obtained in laboratory and through appropriate calculations.

In this case, the most suitable optimization method is the symmetry one (OS).

By applying the optimization and control methodology proposed by FROHR; ORTTENBURGUER (1986) [8], the optimization of regulator results in the following parameters [2]:

<u>Speed Regulator</u>

Gain:	$V_{Rn} = 5$;
Time Constant	$T_n = 460$ [ms];
Feedback filter:	$T_{gn} = 100$ [ms];
Reference value filter:	$T_{gs1} = 460$ [ms];

<u>Current Regulator</u>

Gain:	$V_{Ri} = 0.14$;
Time Constant:	$T_i = 13.11$ [ms];
Feedback filter:	$T_{gi} = 1.5$ [ms];
Reference value filter:	$T_{gs2} = 14.55$ [ms];

<u>Parameters of the Synchronous Motor:</u>

Rated voltage:	$V_{dR}= 230$ [V]
Rated power:	$P_N=2$[kVA]
Rated Speed:	$N_N= 1800$[rpm]
Stator current:	$I_N=5$[A]

IV. MACHINE OPERATION

The commutation in the inverter bridge is possible due to the voltage in the motor terminals; this voltage is a reference to the thyristors trigger pulses. The bridge operates with a fixed trigger angle of 150°, obtained through a special delta zigzag synchronism reference transformer. The thyristor trigger is performed through an algorithm that identifies the correct sequence of the thyristors to be triggered:

$$SA \leftarrow (va>0);$$
$$SB \leftarrow (vb>0);$$
$$SC \leftarrow (vc>0);$$

$$P(1) \leftarrow SA \text{ and not } SB; \qquad P(2) \leftarrow SA \text{ and not } SC;$$
$$P(3) \leftarrow SB \text{ and not } SC; \qquad P(4) \leftarrow SB \text{ and not } SA;$$
$$P(5) \leftarrow SC \text{ and not } SA; \qquad P(6) \leftarrow SC \text{ and not } SB;$$

Where va, vb and vc are the voltage values in the reference transformer phases, obtained through an A/D converter. The variables SA, SB and SC indicate if the voltage signal in the phases is positive or negative.

The vector P(n) represents the state of the pulses in the thyristors. In Figure 8, the hashed area between voltages in phase A and B shows the condition of the pulse trigger in thyristor 1.

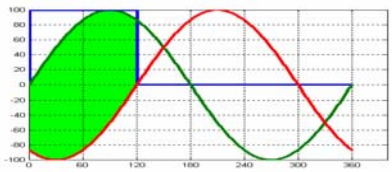

Fig. 8. Condition of the pulse trigger in thyristor 1.

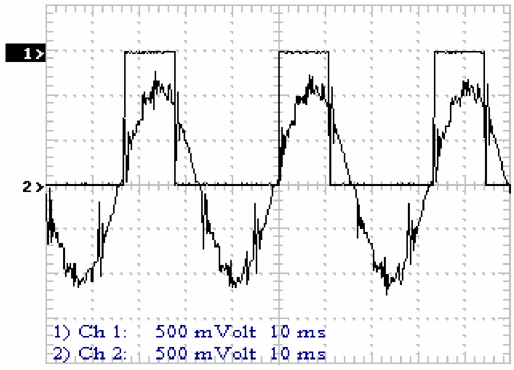

Fig. 9. Voltage in line A and trigger pulse in thyristor 1.

Figure 9 shows the actual voltage signals in line A of the reference transformer and the signal generated for the thyristor 1 pulse, obtained in laboratory. The real scale is 5[Volt/div].

The machine has an independent field current supply which is overexcited to obtain a larger torque for the current injected.

V. START UP AND OPERATION IN LOW SPEED

As mentioned previously, speed is a function of the rectifier circuit trigger angle, which is defined by the speed governor complying with a reference defined by the operator. Under very low speeds, about 10% of the rated speed, the voltage in the machine terminals has a very low value that may not allow the natural commutation of the thyristors. However, when the motor is at rest, there is no voltage in the machine. In these situations, the commutation must be forced, extinguishing the current in the DC link; that is done through changing the trigger angle of the rectifier bridge, forcing it to operate in inverter mode. This operation is software-controlled. Since the governor circuit is analog, the change in the angle was obtained through a summing a DC voltage in the trigger signal making the firing angle to be equal to 150°, in the instants where it is necessary to force the commutation of the inverter bridge.

Despite of that, to be able to start-up the motor there must be a minimum voltage value in its terminals. This is obtained through a start-up routine that arbitrarily triggers a pair of thyristors, injecting a current pulse in the motor windings with a period, experimentally adjusted, to allow the alignment of the rotor with the field generated. Since the torque depends on the rotor position, it is necessary to generate a trigger sequence to guarantee the alignment of the rotor in the position desired. According to the method outlined previously, the commutation must be forced, to change the trigger from a pair of thyristors to the next pair. After that, a new sequence of triggers is generated with a shorter period making the motor reach a minimum value of speed so that the algorithm that identifies the thyristor trigger sequence may work. However, the commutation still is performed by software, whenever the trigger of a thyristor changes. This procedure is maintained until the motor reaches a speed where the natural commutation of the bridge may occur, although the speed governor uses a tachogenerator to obtain the motor speed signal. The inverter trigger software uses the machine voltage signal itself to estimate the speed and allow the start-up procedure to run. Figures 10 and 11 show the software flowchart.

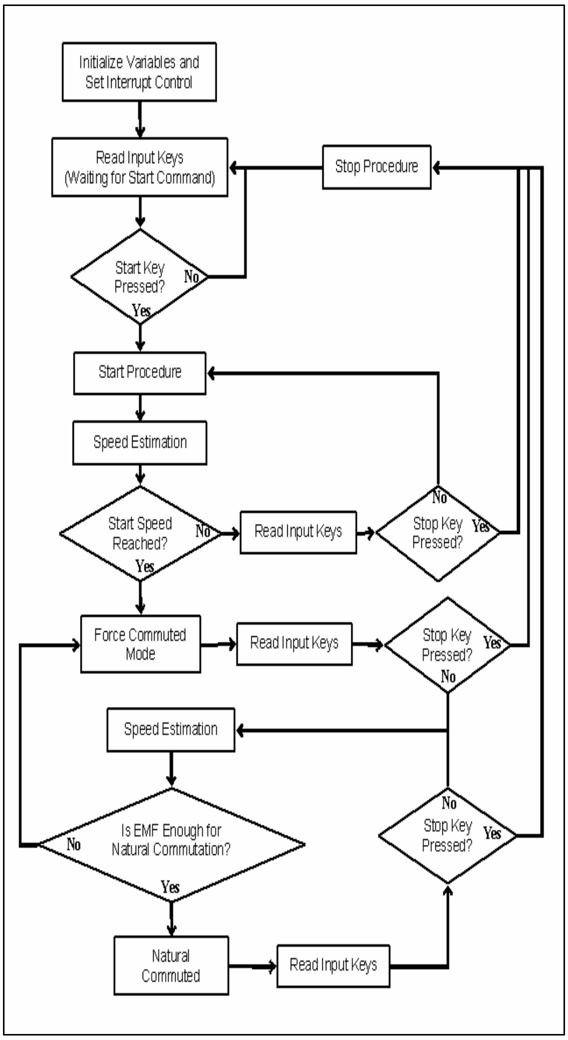

Fig. 10. Control Software (Main Routine).

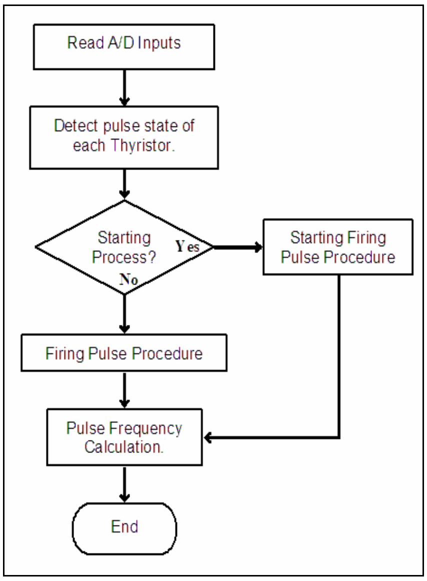

Fig. 11. Interruption Routine.

VI. RESULTS

Figures 12 and 13 below show the results obtained with the driving implemented in laboratory.

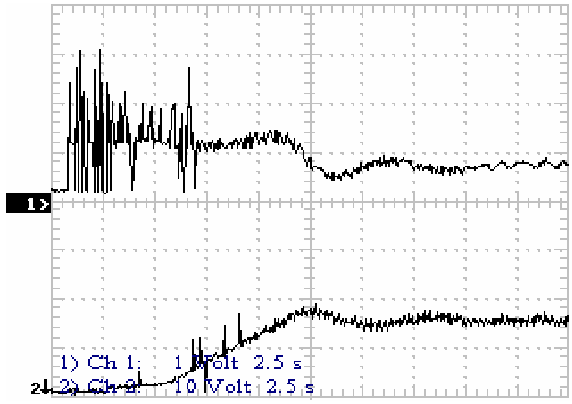

Fig. 12. Start up of the Synchronous Motor.

Figure 12 shows the current variation (top section, the scale is 1[A/div]) and the speed variation (bottom section, the scale is 800[rpm/div]) during motor start up. Figure 13 illustrates the current in the DC link during forced commutation (the scale is 1[A/div]).

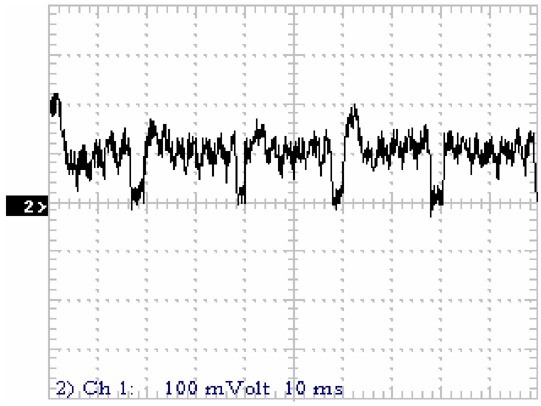

Fig. 13. Current in the DC Link.

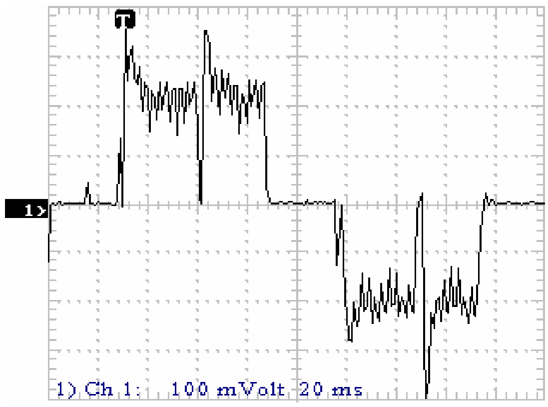

Fig. 14. Current in phase A of SM.

Figure 14 illustrates the current in phase A of the synchronous motor, also during the forced commutation (the scale is 1[A/div]). So as to verify the governor actuation, a load degree was applied on the machine, by using a DC generator coupled to the motor shaft.

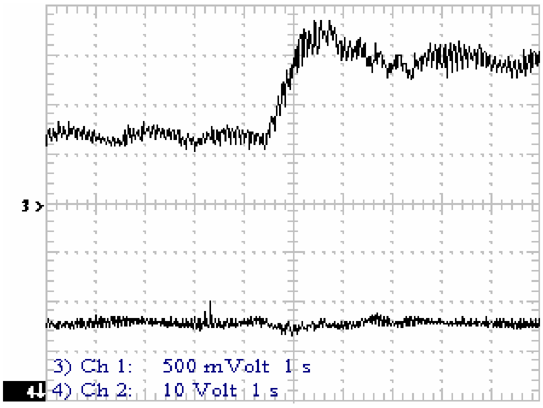

Fig. 15. Load step response.

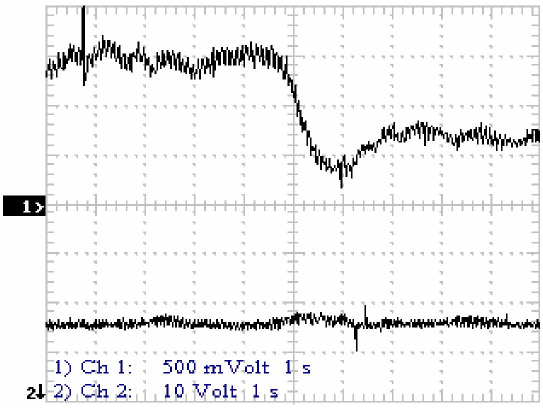

Fig. 16. Withdrawal of load.

Figures 15 and 16, respectively, show the application and withdrawal of load. The top section of the figures shows the current variation in the DC link (the scale is 1[A/div]), while the bottom section shows the motor speed variation (the scale is 800[rpm/div]).

VII. CONCLUSION

The results obtained with this drive were considered satisfactory. The trigger circuit, despite of not using digital filters, shown sufficiently immunity to the noises in the motor voltage, even at low speed. The group formed by the analog control circuit and the trigger micro processed circuit have shown to be functional and satisfactory.

The advance in the microprocessor and microcontrollers technology allowed them to become more and more compact and fast. That added to a significant reduction in their prices. These factors along with the feature of maintenance ease, reduction of the number of components of the circuit and the flexibility offered by the software, made the micro controlled circuits to become a very efficient solution. Although in this paper the trigger control of the inverter bridge has been implemented in C language to run in a desktop using MS-DOS operational system, it was conceived to allow, with the due modifications, the possibility of being implemented in microcontrollers. The data acquisition board used was PCL-711B from Advantech. However, the acquisition was made by using the direct access mode to the input and output ports, without the use of the "driver" supplied by the manufacturer to allow the software to be more hardware-independent.

VIII. REFERENCES

[1]. ADVANTECH Co., Ltda. "PCL-711B - PC-MultiLab User's Manual"; Taiwan : Advantech Co., Ltd., aug., 1993.

[2]. QUINDERÉ, K. E. B. DE – "Implementation of a Controlled Driving System for the Synchronous Machine Using Analog and Digital Governors" – Tese de Mestrado, Escola Federal de Engenharia de Itajubá, 1999. (In Portuguese)

[3]. A. Bellini, G. Franceschini, M. Paladini, N. Petrolini, C. Tassoni, "Low Cost Implementation of

[4]. A Sensorless Control for Synchronous Reluctance Motors", IEEE SDEMPED 2001, Gorizia, September 2001. J. Dixon and I. Leal, "Current Control Strategy for Brushless DC Motors, Based on a Common DC Signal", IEEE Transactions on Industrial Electronics, March 2002.

[5]. A. Jakubowicz, M. Nougaret, and R. Perret, "Simplified Model and Closed-Loop Control of a Commutatorless DC Motor", IEEE Trans. Ind. Appl., vol. IA-16,pp.165-172, Mar./Apr. 1980.

[6]. B. Mueller, T. Spinanger, D. Wllstein, "Static Variable Frequency Starting and Drive System", IEEE/IAS 1979 Annual Meeting, pp. 429-438, 1979.

[7]. E. R. da Silva, L. P.B. de Oliveira, C. B. Jacobina, "Control Techniques Used in Current Supply Inverters with Pulsed Current in DC Busbar", XII Congresso Brasileiro de Automática, pp. 1683-1688, 1998. (In Portuguese)

[8]. F. Fröhr & F. Orttenburger "Introduccion al Control Eletronico", Siemens, Marcombo S/A, Barcelona, 1986.