Variable Speed Refrigeration System with HPF Voltage Source Rectifier

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Abstract – This paper is based on the analysis and implementation of a new drive system applied to refrigeration systems, complying with the restrictions imposed by the IEC standards (Harmonic/Flicker/EMI-Electromagnetic Interference restrictions), in order to obtain high efficiency, high power factor, reduced harmonic distortion in the input current and reduced electromagnetic interference, with excellent performance in temperature control of a refrigeration prototype system (automatic control, precision and high dynamic response). The proposal is replace the single-phase motor by a three-phase motor, in the conventional refrigeration system. In this way, a proper control technique can be applied, using a closed-loop (feedback control), that will allow an accurate adjustment of the desirable temperature. The proposed refrigeration prototype uses a 0.5Hp three-phase motor and an open (Belt-Drive) Bitzer IY type compressor. The input rectifier stage's features include the reduction in the input current ripple, the reduction in the output voltage ripple, the use of low stress devices, low volume for the EMI input filter, high input power factor (PF), and low total harmonic distortion (THD) in the input current, in compliance with the IEC61000-3-2 standards. The digital controller for the output three-phase inverter stage has been developed using a conventional voltage-frequency control (scalar V/f control), and a simplified stator oriented Vector control, in order to verify the feasibility and performance of the proposed digital controls for continuous temperature control applied at the refrigerator prototype.

I. INTRODUCTION

Industrial refrigeration systems can be found in almost every developed location in the world. Applications for these systems include food preservation, heat removal from industrial processes such as chemical production, and numerous other special applications in the construction and manufacturing industries. Vapor compression refrigeration systems have been used to reduce the temperature of a particular substance or process for over one hundred years. However, the industrial refrigeration industry has historically paid very little attention to the energy needed to achieve the objectives of the refrigeration processes [1-2].

In this context, billions of dollars are spent in each year, for example, in the United States on energy for household, automotive and industrial air conditioning and refrigeration (AC&R) devices [3].

In Brazil, AC&R devices for household are responsible for 25% of the total amount of energy consumed in the country. Furthermore, the structure of consumption for this sector is distributed according the following (data obtained from Procel, [4]): refrigeration (refrigerators and freezers) 32%; water heating 26%; lighting 24%, and others 18%.

On the other hand, regarding to household application, the refrigerators and freezers consumption represent about 9% of the total amount of energy consumed in Brazil. In the commercial applications the air conditioning devices represent 20% of the total energy consumption in this sector, which is equal to 3% of national consumption. Finally, the industrial sector uses 46% of the total amount of energy produced in Brazil, and this consumption assumes the following distribution: heating 20%; refrigeration 6%; lighting 2%, and others.

In this context, it is clear that an increase in the efficiency of AC&R systems will bring a notable effect in the energy saving. Additionally, the increasing of efficiency of these systems has a much lager social and environmental impact because of the reduction in the fossil fuels use, required to provide this energy. Significant progress has been obtained in recent years in the improvement of the efficiency of AC&R systems. Thus, with the increasing availability and inexpensive of powerful processing device, significant increase in the efficiency of control techniques is achieved, allowing the implementation of complex digital control techniques.

Conventional refrigeration systems employ single-phase induction motors, with starting capacitor. These conventional systems demand a high starting conjugate, with consequent high inrush currents (resulting in active losses) and present reduced power factor (usually 0.5 up to 0.8), although they present a reduced harmonic distortion in the input current. These traditional systems use control strategies based on single-input single-output (SISO) control or simple on/off ("bang-bang") control for temperature regulation, resulting in constant problems of inrush currents (due to the high conjugate) and consequent active losses, resulting in reduced energy efficiency.

Therefore, such conventional systems do not comply with the restrictions established in international standards, like IEC 61000-3-2 and IEC 61000-3-4, for example. In addition, possible flicker problems (variations in low frequencies of the rms supply voltage, with limits imposed by IEC61000-3-3 standards) and possible voltage sags can be verified in these systems.

Therefore, several researches are focused to fulfill these requirements, in order to eliminate the power quality degradation problems in several AC drives, including the refrigeration systems [5-7].

In this context, a novel single-phase voltage source rectifier capable to achieve High-Power-Factor (HPF), applied to a variable speed refrigeration system application, is proposed in this paper. The proposed system is composed by a single-phase high-power-factor boost rectifier, with two cells in interleave connection, operating in critical conduction mode, and employing a soft-switching technique, controlled by a Field Programmable Gate Array (FPGA), associated with a conventional three-phase IGBT bridge inverter (VSI – Voltage Source Inverter), controlled by a Digital Signal Processor (DSP). The soft-switching technique for the input stage is based on zero-current-switching (ZCS) cells, providing ZC (zero-current) turn-on and ZCZV (zero-current-zero-voltage) turn-off for the active switches, and ZV (zero-voltage) turn-on and ZC (zero-current) turn-off for the boost diodes [8]. The disadvantages related to reverse recovery effects of boost diodes operated in continuous conduction mode (additional losses, and electromagnetic interference (EMI) problems) are minimized, due to the operation in critical conduction mode [8-11]. In addition, due to the interleaving technique, the rectifier's features include the reduction in the input current ripple, the reduction in the output voltage ripple, the use of low stress devices, low volume for the EMI input filter, high input power factor (PF), and low total harmonic distortion (THD) in the input current, in compliance with the IEC61000-3-2 standards. On the other hand, a digital control based on programmable logic devices, such as FPGAs, can use the recent advances in digital design methodologies, where hardware description language (VHDL) allows the descriptions of digital systems using their behavior models [12-15]. Therefore, the digital controller for the input stage has been developed using a hardware description language (VHDL) and implemented using a XC2S200E-SpartanII-E/Xilinx FPGA device, performing a true critical conduction operation mode for two interleaved cells, and a closed-loop to provide the output voltage regulation, like as a HPF pre-regulator rectifier. The digital controller for the output stage, conventional three-phase IGBT bridge inverter stage, has been developed using a digital signal processor (DSP) and implemented using a TMS320F2812/Texas Instruments device. The conventional Voltage-Frequency control (scalar V/f control), and a Simplified Stator Flux Vector Oriented Control were implemented, in order to provide speed control of a Bitzer IY type compressor, for continuous temperature control applied at a developed refrigerator prototype, with the main objective to verify the feasibility and performance of the proposed digital controls.

II. THE PROPOSED SYSTEM

In order to validate the new proposed structure, an application was chosen for refrigeration system with 0.5HP three-phase induction motor and an open type Bitzer alternative compressor, as shown in Fig. 1(a).

For this specific power level, the input stage HPF voltage source rectifier is a single-phase structure. However, for high power applications, the proposed technique can be easily adapted, considering single-phase, or, three-phase input stages.

According to Fig. 1, this new proposed system allows the operation in a universal range for the AC input voltage ($97V_{rms}$-$260V_{rms}$), with the input power factor nearly the unity, and the harmonic distortions in the input current in compliance with the IEC61000-3-2 standards.

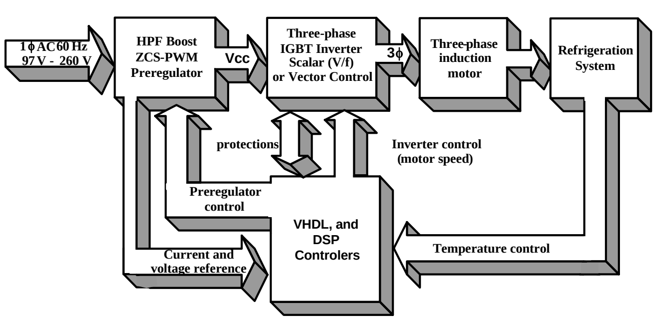
The proposed input stage, shown in Fig. 1(b), can reduce significantly the switching losses, including the diode reverse recovery losses, performing high efficiency, high power density, and lower EMI emission [8].

The output stage is composed by a conventional three-phase IGBT bridge inverter (Three-phase Voltage Source Inverter), using digital control implemented in a DSP-TMS320F3812, in order to impose the desirable speed control for the three-phase induction motor, and continuous temperature control in a developed refrigerator prototype, through the use of an open (Belt-Drive) Bitzer IY type compressor.

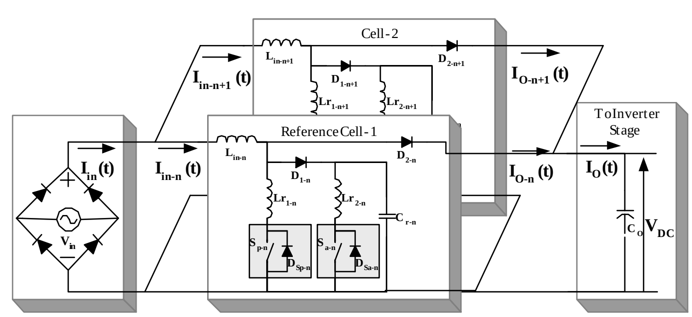
III. DIGITAL CONTROL STRATEGIES

Figure 2 shows the control algorithm for the input stage HPF interleaved rectifier. It has been developed using a hardware description language VHDL. The FPGA XILINX device XC2S200E-pq208-6C was employed and mounted in a prototype board D2E from DIGILENT Inc.

The peak-current control is employed to turn-off the main switches. Thus, when the current through one main switch reaches a given reference value, its gate signal is set to low level.



(a)Blocks Diagram for the proposed variable speed refrigeration system.



(b)Input Stage, HPF Voltage Source Interleaved Boost Rectifier.

Fig.1 – The proposed variable speed refrigeration system, with continuous temperature control, and compliance with the IEC61000-3-2.

The voltage compensator is one-zero two-pole PI compensator with one pole at the origin, the other at high frequency and one zero at low frequency, as shown in Fig. 2.

Figure 3(a) shows the block diagram of the output stage using volts/Hz control of the three-phase induction motor, and include the power subsystem and the signal processing subsystem. The power subsystem is composed by: i) the DC link voltage V_{DC}, which is generated by the previously described single-phase high-power-factor boost rectifier; ii) the three-phase PWM voltage source inverter; iii) induction motor. No low pass filter is necessary at the inverter output since the motor inductance already is capable of getting rid of the high frequencies components of the inverter output voltage. The signal processing subsystem is the one necessary to do the voltz/Hertz control, and it is composed by: i) feedback signal estimator, which uses the current and voltage machine terminal to estimate the rotor speed, used in the speed control loop; ii) the PI speed controller; iii) the PWM modulator. The PWM signals, generated by the PWM modulator is used to control the voltage fed inverter.

Figure 3(b) shows the block diagram of the output stage using stator flux oriented vector control. The power subsystem remains the same, while the signal processing subsystem is somewhat more complex. It is composed by the feedback signal estimation, which uses the machine terminals voltages and currents to estimate all necessary signals for the controllers and for the voltage vector orientation.

It is also part of the signal processing subsystem the controller, which has speed and stator-flux control in the outer loops. The speed control loop has a current control as inner loop. The flux loop output is added with the decoupling compensation current to establish the direct current command. The synchronous current control loops then generate the signals v_{ds}^* and v_{qs}^*, which are vector rotated with the help of unit vector angle to generate V* and θ*, the inputs of the PWM modulator. Finally, as in the volts/Hz control, there is the PWM modulator.

The two proposed control algorithms, volts/Hz control and stator flux oriented vector control, were modeled using SIMULINK/Matlab.

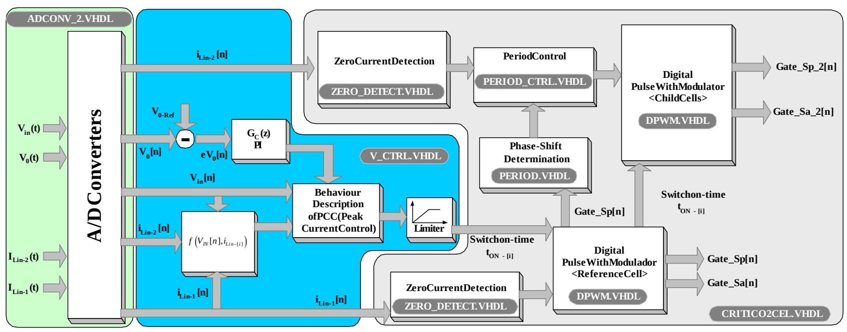
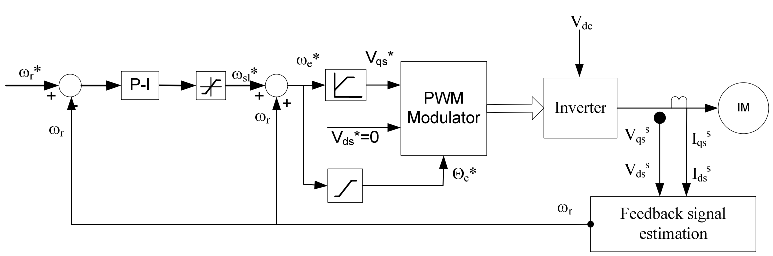
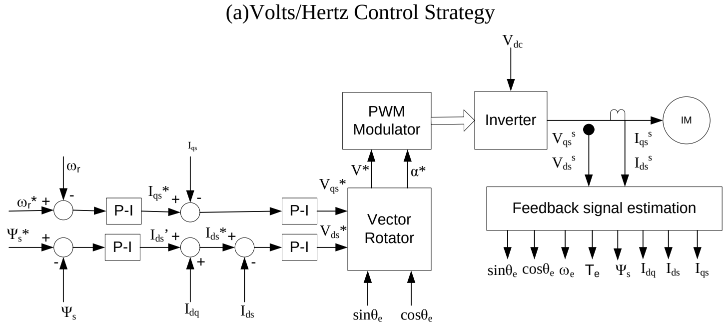


Fig. 2 – Blocks diagram of the control algorithm for the input stage HPF voltage source interleaved rectifier.



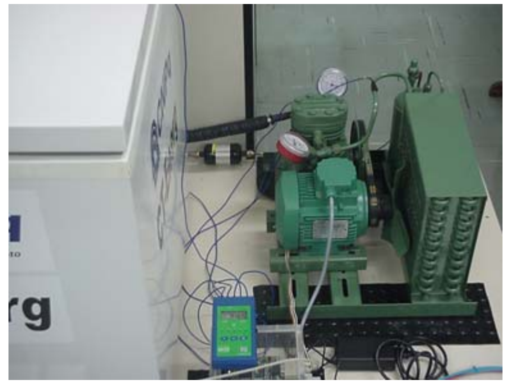
(a)Volts/Hertz Control Strategy



(b) Stator Flux Oriented Vector Control Strategy

Fig 3 – Blocks diagram of the control algorithms for the output stage Three-phase IGBT Voltage Source Inverter.

(a)Details – Complete system: Rectifier and Inverter Stages



(b) Details – Temperature and Pressure Sensors

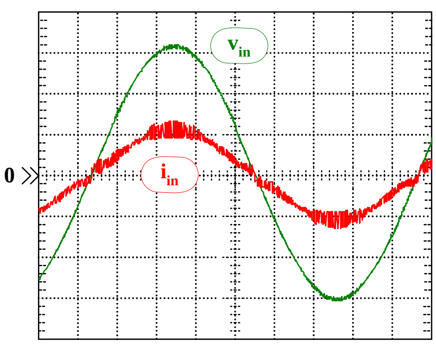
Fig 4 – The implemented variable speed refrigeration system.

TABLE I – PARAMETERS OF THE INPUT STAGE, HPF VOLTAGE SOURCE RECTIFIER.

Input and Output Requirements	
Parameter	**Specification**
$V_{in[rms]}$	220 V
V_{DC}	400 V
P_O	1 kW
$f_{s[Quiescent\ Point]}$	50 kHz
Number of Cells (N)	2
Phase-Shift [rad]	$\pi/2$

Where: [i] is the number of ZCS boost interleaved cell

Circuit Parameters	
Parameter	**Specification**
$S_{P1\text{-}i}$	HGTP12N60A4D
$S_{A1\text{-}i}$	HGTP7N60A4D
$D_{1\text{-}i}$	RHRP860
$D_{2\text{-}i}$	RHRP8100
$L_{in\text{-}i}$	428.5μH
$L_{r1\text{-}i}$	28.6μH
$L_{r2\text{-}i}$	20.0μH
$C_{r\text{-}i}$	10.0nF
Co	390.0μF



v_{in}: 100V/div; i_{in}: 5A/div, 2ms/div.

Fig. 5 - Input current and voltage for the proposed HPF interleaved rectifier, during one ac line period, at nominal load.

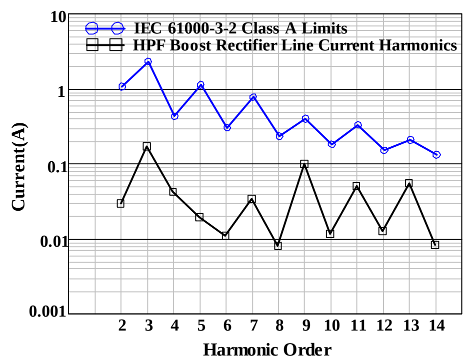


Fig. 6 – Harmonic current amplitudes from the proposed HPF interleaved rectifier, and the IEC61000-3-2 Class A Limits.

IV. SIMULATION AND EXPERIMENTAL RESULTS

Considering the thermodynamic modeling, the simplest compression cycle operates with four components: compressor, condenser, expansion valve, and evaporator. The fluid enters the compressor as a superheated vapor at a low pressure. The fluid is compressed to a high pressure by the compressor and then enters the condenser. At higher pressure, the fluid has a higher temperature than the ambient conditions, and as a fan blows air across the condenser, heat is transferred to the air, and the fluid condenses. The fluid leaves the condenser as a sub-cooled liquid at high pressure. Then, the fluid passes through an expansion device, and at the exit of the expansion valve, the fluid is generally two-phase, and at low pressure. Then the fluid enters the evaporator. At lower pressure the fluid has a lower temperature than the ambient conditions. Thus, heat is transferred to the fluid, and it evaporates. The fluid leaves the evaporator as superheated vapor and enters the compressor.

Figure 4 shows details for the implemented variable speed refrigeration system, with continuous temperature control, and compliance with the IEC61000-3-2 standards, considering the use of one conventional refrigeration system employing a Bitzer IY type compressor with R22 refrigerant.

The input and output data, including the designed parameters and components for the input stage HPF voltage source rectifier are summarized in Table I. The output stage was implemented using a 0.5HP three-phase induction motor by Sieber, and a 0.75kVA three-phase PWM IGBT bridge voltage source inverter.

The input current and voltage for the proposed input stage HPF voltage source rectifier are shown in Fig. 5, at rated load. It can be observed in Fig. 5 that the input current waveform is practically in phase with the input voltage waveform due to interleaving technique used. Thus, the experimental power factor measured for nominal load condition was equal to 0.989. The THD (Total Harmonic Distortion) for the input current was equal to 5.33%, and in agreement with the limits of Class A - IEC61000-3-2 standards, as shown in Fig. 6.

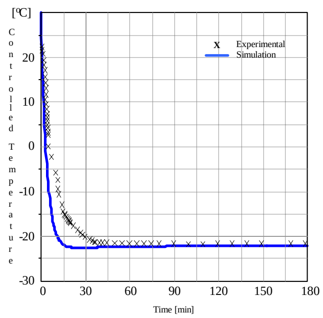
One can observe in Figs. 5 that the interleaving technique eliminates the discontinuity in the input current, providing conditions to reduce the EMI input filter.

Figure 6 shows the main simulation results obtained from the dynamic thermodynamic model for the system, and its correspondent experimental results, considering the compressor operating with 1350rpm. It should be noticed that the used dynamic thermodynamic model was based on the models proposed in [1-3].

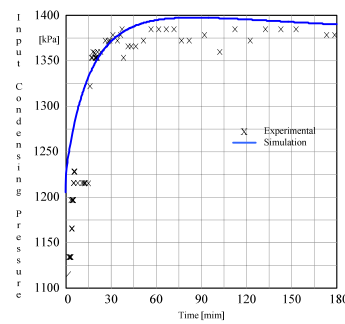
Figures 7 and 8 show the results for the proposed control, considering the operation using the volts/hertz control strategy. As one can verify in figs. 7(a), and 7(b), the controllability test has shown that the control strategy and proposed algorithm are feasible, in order to obtain the desirable controlled temperature. The proposed algorithm was developed based on the blocks diagram shown in fig. 9, in order to impose a desirable value for the controlled temperature inside the refrigerator.

Figures 10, and 11 show the V/Hz control and the vector control techniques, respectively, implemented in the MatLab-Simulink.

The experimental results for the refrigeration system operation using the volts/hertz and simplified stator flux oriented vector control strategies are shown in Fig. 12.

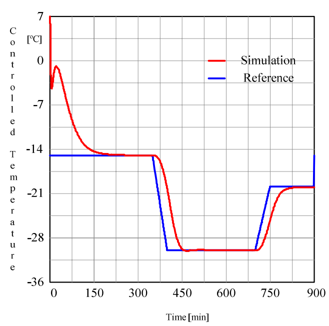


(a)

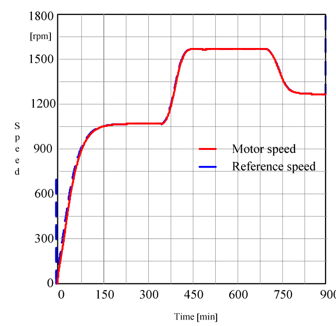


(b)

Fig. 7 – Simulation and experimental results for the: (a) Controlled Temperature, and (b) Input pressure in the condenser, considering operation with 1350rpm.



(a) Controlled Temperature



(b) Motor speed and its reference speed

Fig. 8 – Results for the proposed control, considering the operation using the Volts/Hertz control strategy.

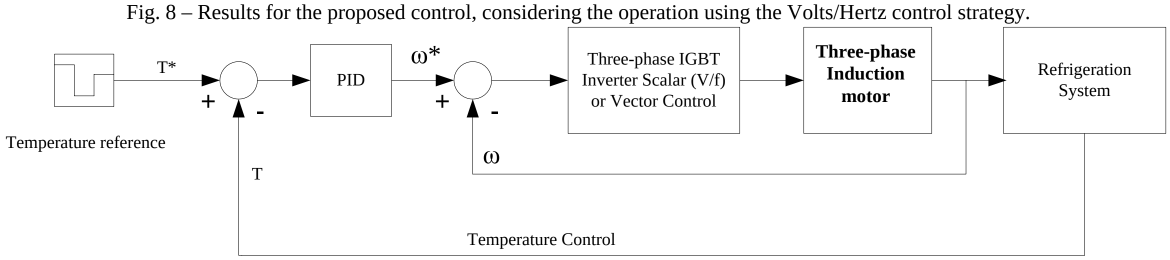


Fig. 9 – Blocks diagram to impose a desirable value for the controlled temperature of the refrigerator, considering variable speed operation for the induction motor.

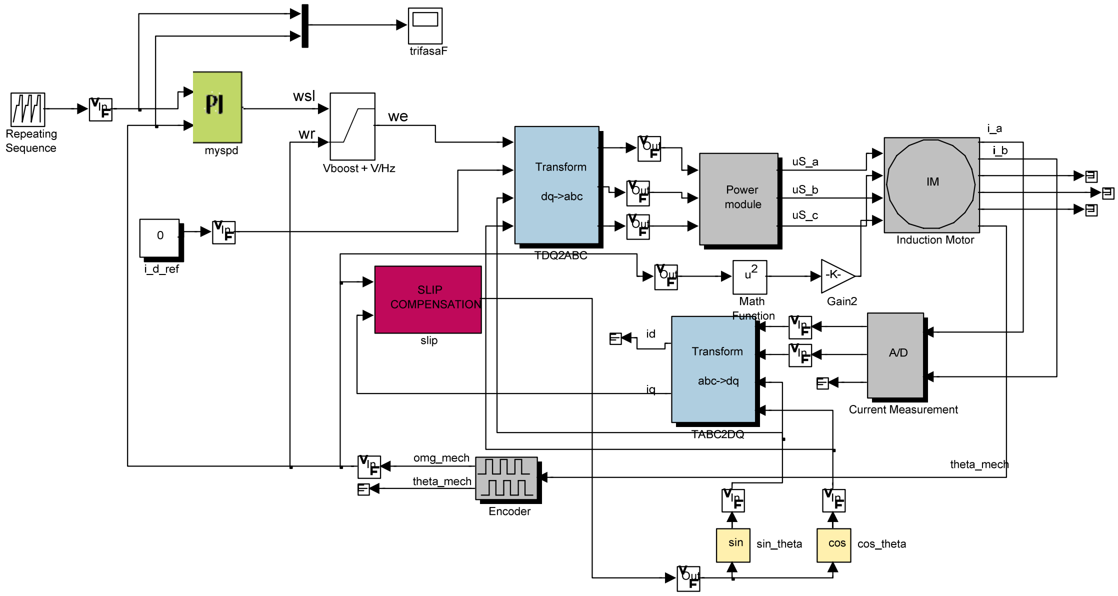


Fig. 10. – The V/Hz control technique implemented in the MatLab-Simulink.

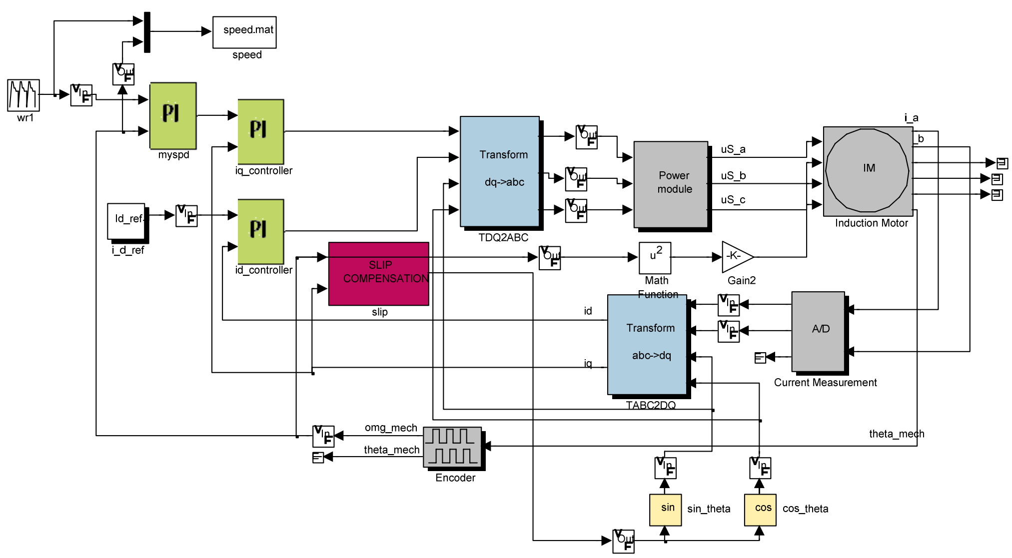
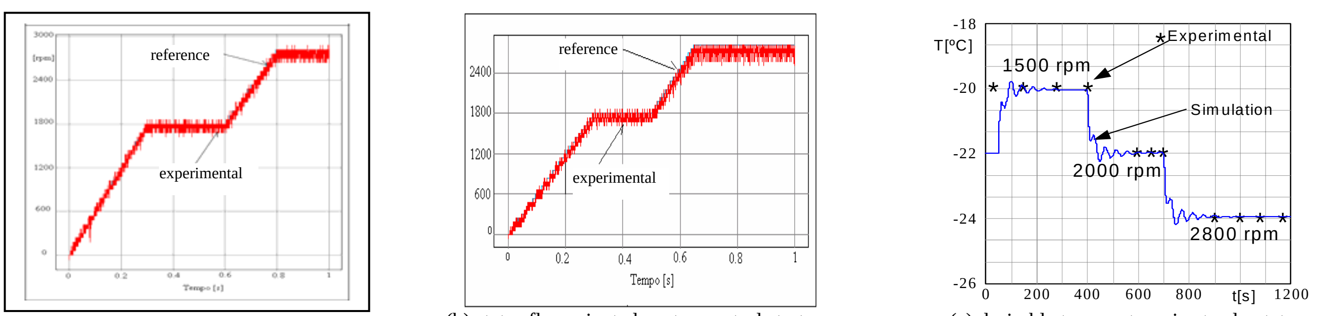


Fig. 11. – The vector control technique implemented in the MatLab-Simulink.



(a) Volts/Hertz control strategy

(b) stator flux oriented vector control strategy

(c) desirable temperature, in steady-state

Fig. 12. – Experimental Results for the proposed controls: considering the operation using the Volts/Hertz control strategy and stator flux oriented vector control strategy, and the controllable/desirable temperature in steady-state.

Analyzing the experimental results, one can observe that during a vapor compression operation, the machine performance and energy efficiency are closely dependent on the thermodynamic states of refrigerant at various components in the cycle loop, including evaporating pressure, condensing pressure, superheat at the evaporator outlet, and sub-cool at the condenser outlet. The proper regulation of these thermophysical variables and their dynamic behavior can lead to high performance and energy-efficient operation of the refrigeration system. Therefore, this research can be improved considering the use of an electronic expansion valve, in order to control the thermodynamic compression cycle and its efficiency.

V. CONCLUSIONS

In this paper was analyzed a novel single-phase voltage source rectifier capable to achieve High-Power-Factor (HPF), applied to a variable speed refrigeration system, with continuous temperature control, and in compliance with the IEC61000-3-2 standards.

The input stage interleaved boost rectifier was designed at a 1kW nominal output power, using two cells in interleave connection, operating in critical conduction mode, and employing a non-dissipative commutation cells. The proposed interleaved ZCS boost pre-regulator can further reduce the switching losses, including the diode's recovery losses, because all semiconductor devices employed in this proposed rectifier perform soft-commutation processes. Moreover, these commutations are preserved during the ac line period and load variation. In this context, it would be useful for high switching frequency operation and EMI reduction.

The experimental results presented in this paper show that the input power factor is nearly the unity and the harmonic distortions verified in the input current are in agreement with the restrictions imposed by the IEC61000-3-2 standards, for class A equipments.

The digital control for the input stage was implemented using a single programmable logic device FPGA and hardware description language VHDL. The functionality of the controller was verified in this paper, performing a true interleaved operation in critical conduction mode for two interleaved cells, and output voltage regulation.

The digital controller for the output stage, implemented using a conventional three-phase IGBT bridge inverter stage, was developed using a digital signal processor TMS320F2812/Texas Instruments device.

The simulation and experimental results for the conventional Voltage-Frequency control (scalar V/f control) were presented, demonstrating the feasibility for the developed control strategy, in order to provide the speed control of a Bitzer IY type compressor, through a three-phase induction motor, for continuous temperature control of a implemented refrigerator prototype.

Finally, the typical slow time dynamic behavior presented by the refrigeration system in analysis, as are shown in Figs 7 and 9, emphasize that the use of vector control in this application is not considered necessary. Therefore, the scalar control strategy can completely handle all speed changes required for temperature control in the refrigeration system, but in specific applications the vector control should be a requirement.

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