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FPGA-based startup for AC electric drives: Application to a greenhouse ventilation system

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ABSTRACT

In this work, a simplified startup method for AC synchronous machines is solved by means of a simplified algorithm based only in feeding the AC synchronous machine with stator voltages with a ramp frequency. The implementation of the algorithm along with the Space Vector Pulse Width Modulation technique is carried out by means of a Field Programmable Gate Array (FPGA) device, where Very High Speed Integrated Circuit, Hardware Description Language (VHDL) modules are custom designed. Experimental results were carried out for the ventilation of a greenhouse. The fan drive is turned on according to an existing control strategy designed for an optimal ventilation of the greenhouse. The designed algorithm with custom VHDL modules yields to a great performance for the fan drive in terms of smooth transient currents. The proposed algorithm was also implemented with an embedded microprocessor or softcore in an FPGA device for comparison purposes, yielding to same results. But in the case of optimal utilization of FPGA resources and the speed of execution of the algorithm, the VHDL modules custom design showed the best results.

1. Introduction

Electrical drives [20,29] can be classified into two groups: Alternate Current (AC) an Direct Current (DC) machine drives. DC machine drives are very popular due to a high torque, high efficiency, and are controlled by adjusting the magnitude of the supply voltage. Some drawbacks of these motors are the service requirements and the relative high costs. On the other hand, three-phase AC machines can be classified in asynchronous, synchronous and variable reluctance machines. The asynchronous or induction motor (IM) is a popular machine widely used in industrial drive systems [3,6], due to their simple mechanical construction, low service requirements, and lower costs with respect to DC motors. Synchronous machines are classified in sinusoidal, brushless and reluctance machines, where the most popular are the sinusoidal which is characterized by a sinusoidal Back Electro-Motive Force (BEMF) and the brushless that is characterized by a trapezoidal BEMF and by using permanent magnets [23]. The sinusoidal motor is classified depending on the manner the magnetic field is provided: wound field motors and Permanent Magnet Motors (PMM) [5,7,22], where PMM are at the same time classified in surface mounted PMM and interior mounted PMM. In particular, PMM have attracted the attention of control engineers practitioners due to its properties as high efficiency, minimal maintenance requirements and high torque-inertia ratio, therefore they are widely used in household appliances and in several industrial fields [18] with applications as fans, pumps and compressor type loads.

The startup of three-phase AC motors by directly being connected to a line voltage is not the best way due to large transient current values. Hence, there are several methods for the startup of electric motors, where common methods are [9]:

- *Direct start method*, connects the motor directly to the line voltage but can only be applied to asynchronous motors;
- *Reduced voltage starting*, also known as *soft start* is commonly carried out with thyristors where the firing angle is linearly incremented resulting in a voltage ramp that can go from zero to full voltage.
- *Soft start with control*, consists in adding to the soft start method a current limiter by means of a control loop;

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The direct start is a common method used in industrial process but the energy consumption can not be satisfactory due to large transient current values. The soft start method reduces the acceleration torque produced by the motor, as a consequence more time is required to move the load. Soft start with control can significantly reduce large transient current values by adding complexity to the startup algorithm. The direct start method when applied to an AC synchronous motor may be accompanied with a temporary reverse rotation or may lead to a starting failure. The AC synchronous motor can be accelerated from standstill to a certain speed by applying a ramp frequency signal into the stator voltages in a similar fashion as in the well known scalar *V*/*f* control method [1]. The drawback of the *V*/*f* control technique is that requires of an extra circuitry and a control logic for the regulation of the voltage magnitude.

In general, in supplying voltages to AC motors (generated in open-loop or closed-loop), a three-phase inverter is required and a digital device capable of generating the Space Vector Pulse Width Modulation (SVPWM) technique. The SVPWM technique is becoming a popular modulation technique for three-phase AC motors due to the fact that it reduces the total harmonic distortion [28]. Nowadays, digital microprocessor technology [27] make feasible the implementation of SVPWM techniques for the digital generation of approximated sinusoidal signals. Digital devices as microprocessors or Digital Signal Processors (DSP) [26] are software-based devices where algorithms are executed in sequence. Since instructions are interpreted line by line, intrinsic time delays can lead to a poor performance. Also, computational resources are reduced with SVPWM algorithms due to the fact that some resources are devoted to periodic timing events such as sampling, SVPWM algorithm calculation and gating signals generation, making difficult to incorporate other algorithms. An alternative approach is the use of Field Programmable Gate Arrays (FPGA) [10,13], for implementing the SVPWM algorithm. The advantages of these devices are due to the fact that it is a hardware-based technique where some set of instructions can be executed in parallel, rapid prototyping, simpler hardware and software designs, high speed performance and reutilization of blocks for future designs.

Due to its features, an FPGA device is considered as an appropriate solution that can handle the computational burden of a SVPWM algorithm. Recent researches regarding the implementation of the SVPWM algorithm in FPGA devices have been reported in the literature. In [12], multilevel SVPWM algorithms are analyzed and implemented into an FPGA by means of Matlab® and Xilinx® System Generator for Simulink, where optimization of algorithms is not performed. A shifted SVPWM method to improve the operation of dc-link resonant inverters is partially implemented in a DSP and a FPGA device in [16]. In [14] a variable common mode rejection pulse width modulation algorithm for a neutral point clamped inverter is implemented in an FPGA. Such implementation is not described, only the illustration of the main RTL schematic diagram is provided, making it difficult in that way to reproduce the reported results. The reader can find a complete survey of FPGA design methodology for industrial control systems as presented in [13], for the control of AC machine drives in [15], for the tuning of control systems in [8,18], and for control of industrial applications in [17,19,21].

One of the industrial applications where the assisted startup of AC electric drives is necessary, is with fan drive systems employed in greenhouses. In warm regions and during the day, an excessive accumulation of heat inside greenhouses is registered. This particular problem was solved in [2] by reducing the heat inside a greenhouse in an efficient way, consisting in solving an energy optimization problem which was stated in the following manner: ¿How to maintain the inner temperature of a greenhouse under an established bound and, at the same time, minimize the time lapse that the fan drives are turned on, and consequently reduce the consumption of energy? Although in [2] the time lapse that the fan drives are turned on is minimized, the startup of these drives are carried out with the direct start method, resulting in large transient currents each time the motor is turned on.

Hence, based on all of the above exposed, the objectives of this work are to present a simple startup method design for the broad class of AC synchronous machines, relying on supply voltages with a ramp-shape frequency. Also to present the implementation design of the supply voltages along with the SVPWM algorithm in a FPGA with a Very High Speed Integrated Circuit, Hardware Description Language (VHDL) custom design. Finally, to present the real-time results when the synchronous machine is used as a fan drive for the heat reduction in a greenhouse.

The rest of this work is of the following form: Section 2 deals with the startup algorithm for AC synchronous machines. Section 3 shows the FPGA implementation of the proposed startup algorithm along with the SVPWM algorithm. Experimental results are shown in Section 4 and finally some comments conclude the work in Section 5.

2. Startup of AC synchronous machines

In particular, synchronous PMM have a three-phase stator winding and a rotor with surface or interior mounted permanent magnets. Surface mounted PMMs are for low velocity applications and interior mounted PMM for higher velocities. In the case of wound field synchronous motors, the magnetic field is provided by a field winding in the rotor where a mechanical commutator is necessary as in DC motors. In any case, the induced torque of AC synchronous machines is as follows [4]: $\tau_{\text{ind}} = \text{k}B_R \times B_S$ where B_R and B_S are the rotor and stator magnetic fields respectively. At standstill, when the stator is connected to a three-phase power supply of frequency f, the magnetic field of the stator B_S starts to rotate meanwhile the magnetic field of the rotor B_R is stationary. Fig. 1 illustrates the interactions between B_R and B_S in a cycle of duration $1/f$. It can be appreciated that the average induced torque in one cycle is zero, where the motor is characterized by severe vibrations followed by excessive heating.

Therefore if at initial time, the frequency fed to the stator is slowly increased, then the average torque will be $|\tau_{ind}| > 0$ and the motor will start to accelerate in each cycle, until a nominal velocity is reached.

Synchronous machines rotate to a synchronous velocity, i.e., the rotor velocity is uniquely related to the supply frequency provided in the stator voltages by the following relation [4]:

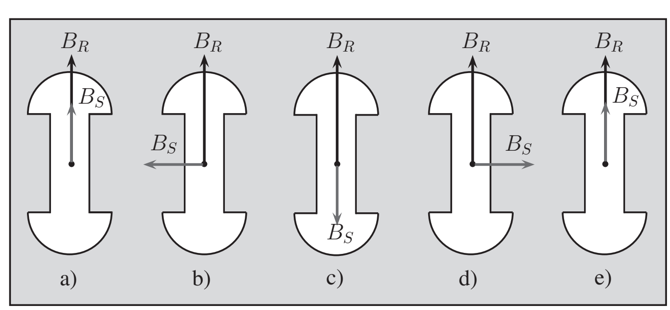

Fig. 1. Magnetic field alignments during one electrical cycle of duration $1/f$. (a) At time $t = 0$ *s* the induced torque is $\tau_{ind} = 0$. (b) At time $t = 1/(4f)$ *s* the induced torque is $\tau_{ind} > 0$. (c) At time $t = 1/(2f)$ *s* the induced torque is $\tau_{ind} = 0$. (d) At time $t = 3/(4f)$ *s* the induced torque is $\tau_{ind} < 0$. (e) At time $t = 1/f$ *s* the induced torque is $\tau_{ind} = 0$.