Dynamically Reconfigurable Control Structure for Three Phase Induction Motor Drives

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ABSTRACT

Field Programmable Gate Arrays (FPGAs) are a suitable hardware platform for the industrial control systems. These dynamically reconfigurable FPGAs can be used as an alternative digital solution to conventional microcontrollers and DSPs to ensure fast operation. This paper presents the feasibility of embedding the Direct Torque Control with Space Vector Modulation (DTC-SVM) of an induction motor into FPGA.The DTC-SVM of induction motor drives is simulated in a Matlab/Simulink environment using a Xilinx System Generator.

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1. INTRODUCTION

The direct torque control with space vector modulation (DTC-SVM) based induction motor drives have been rapid expansion in recent years. The SVM-DTC with low pass filter features constant switching frequency, low torque and flux ripple and low current distortion [1-4].

Digital Hardware Implementation of electrical motor controllers demands a perfect satisfaction of the required performances. In fact, in many industrial applications, such as automotive, space and aircraft systems, the most important performance criteria are as follows:

1) High-level of integration and density of the used target for the control implementation:
2) Embedded low-cost systems based on fully integrated controllers, which ensure several control tasks by the same device;
3) Use of high-performance control algorithms;
4) Flexibility to modify controller strategy and parameters;
5) Fast implementation time by using an appropriate design methodology;
6) Fast real time computation;
7) Reliability, accuracy and safety in harsh environment [5-8].

Field programmable gate arrays (FPGAs) are digital integrated circuits (ICs) that contain configurable (programmable) blocks of logic along with configurable interconnects between these blocks. Design engineers can configure (program) such devices to perform tremendous variety of tasks.FPGAs are often used to prototype ASIC designs or to provide a hardware platform on which to verify the physical implementation of new algorithms. However, their low development cost and short-time to market mean that they are increasingly finding their way into final products [6], [7].

By the early-2000s, high performance FPGAs containing millions of gates had become available. Some of these devices feature embedded microprocessor cores, high-speed input/output (I/O) interfaces, and the like. The end result is that today’s FPGAs can be used to implement just about anything, including communications devices and software-defined radios, radar,image, and other digital signal processing(DSP) applications; all the way up to system-on-chip(SoC) components that contain both hardware and software elements[8].

2. PRINCIPLES OF DTC-SVM

The SVPWM based DTC is based on load angle control strategy and significantly overcomes the most important drawbacks of conventional DTC [9-11]. A single space vector that represent the usual space vector transformation apply to a three phase voltage system is defined as

$$u_s = \frac{2}{3}(u_a + au_b + a^2u_c) \qquad (1)$$

Where $a = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$ and, it is possible to obtain a simple equations set that describe the induction motor dynamic behavior in a stator fixed coordinate system. These equations are:

$$\overline{u_s} = R_s\overline{i_s} + \frac{d\overline{\Psi_s}}{dt} \qquad (2)$$

$$0 = R_r.\overline{i_r} - j.\omega m\overline{\Psi r} + \frac{d\overline{\Psi_r}}{dt} \qquad (3)$$

$$\overline{\Psi_s} = L_s.\overline{i_s} + Lm.\overline{i_r} \qquad (4)$$

$$\Psi_r = L_r.\overline{i_r} + L_m.\overline{i_s} \qquad (5)$$

The basic relation between torque and machine fluxes is:

$$T_e = -\frac{3}{2}P\frac{kr}{\sigma Ls}[\overline{\Psi_s} X \overline{\Psi_r}]$$

$$T_e = -\frac{3}{2}P\frac{kr}{\sigma Ls}|\Psi_s|.|\Psi_r|\sin(\delta) \qquad (6)$$

Where δ , known as load angle between stator and rotor fluxes as shown in figure 1.

A space vector modulation algorithm is used to apply the required stator voltage vector. It is expected that torque ripple is almost eliminated, while zero steady state error is achieved with fixed switching frequency. With one PI regulator, a simple flux calculation block and no rotating coordinate transformation making the control strategy a straightforward application of equation(6). This is illustrated by the control block diagram of Figure 2.

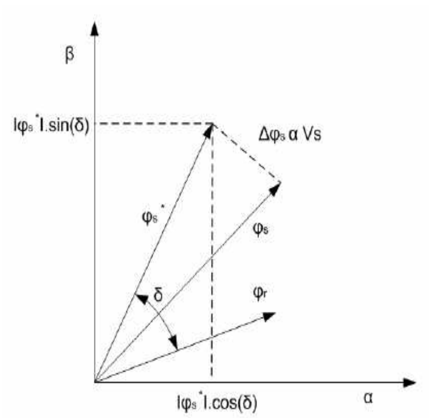

Figure 1. Reference and estimated flux relations

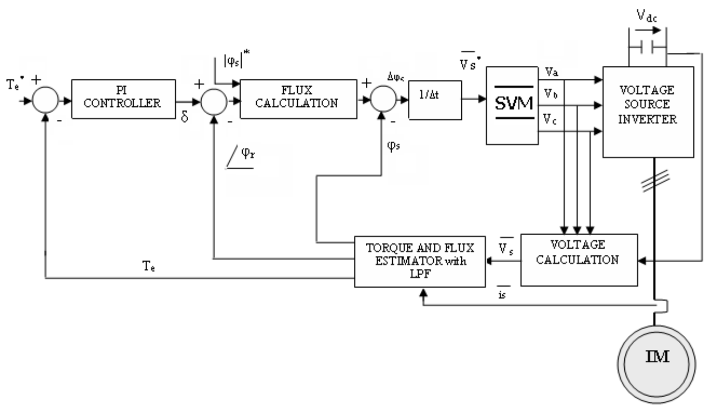

Figure 2. Block scheme of DTC-SVM with closed loop torque control

2.1 Space Vector Modulation (SVM)

The circuit model of a typical three-phase voltage source PWM inverter is shown in Figure 3.S_1 to S_6 are the six power switches that shape the output, which are controlled by the switching variables a, a′, b, b′, c and c′. When an upper transistor is switched on, i.e., when a, b or c is 1, the corresponding lower transistor is switched off, i.e., the corresponding a′, b′ or c′ is 0.Therefore, the on and off states of the upper transistors S_1, S_3 and S_5 can be used to determine the output voltage [12-14].

The relationship between the switching variable vector $[a, b, c]^t$ and the line-to-line voltage vector $[V_{ab}\ V_{bc}\ V_{ca}]^t$ is given in the equation (7)

$$\begin{bmatrix} Vab \\ Vbc \\ Vca \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{7}$$

Also, the relationship between the switching variable vector $[a, b, c]^t$ and the phase voltage vector $[Va, Vb, Vc]^t$ can be expressed below as in equation (8).

$$\begin{bmatrix} Van \\ Vbn \\ Vcn \end{bmatrix} = \frac{Vdc}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{8}$$

There are eight possible combinations of on and off patterns for the three upper power switches. The on and off states of the lower power devices are opposite to the upper one and so are easily determined once the states of the upper power transistors are determined.

According to equations (7) and (8), the eight switching vectors, output line to neutral voltage (phase voltage), and output line-to-line voltages in terms of DC-link Vdc, are given in Table 1.

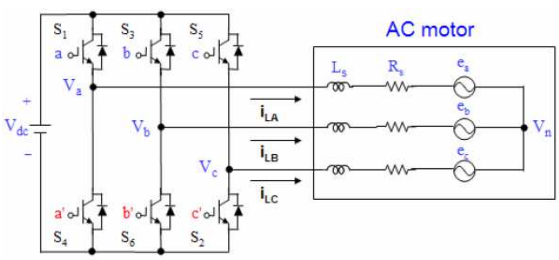

Figure 3.Three-phase voltage source PWM Inverter

Table 1. Switching Vector Table

Voltage Vectors	Switching Vectors			Line to Neutral Voltage			Line to Line Voltage		
	a	b	c	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
V_0	0	0	0	0	0	0	0	0	0
V_1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V_2	1	1	0	1/3	1/3	-2/3	0	1	-1
V_3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V_4	0	1	1	-2/3	1/3	1/3	-1	0	1
V_5	0	0	1	-1/3	-1/3	2/3	0	-1	1
V_6	1	0	1	1/3	-2/3	1/3	1	-1	0
V_7	1	1	1	0	0	0	0	0	0

2.2 PI Controller

PI controllers are found in large numbers in all industries. They come in many different forms. PI controllers are also embedded in all kinds of special purpose control system. These controllers have several important functions: they provide feedback, they have the ability to eliminate steady state error [14].

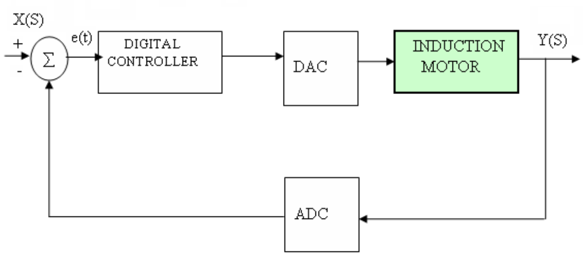

Figure 4. Block diagram of PI Control system

The block diagram of the torque control loop is shown in figure 4.The transfer function of digital PI controller is given as follows

$$H(s) = \frac{Y(s)}{X(s)} = K_P\left(1 + \frac{1}{sTi}\right) \quad (9)$$

Where: K_P- controller gain, T_i-controller integrating time.

2.3 Torque and Flux Estimator with Low Pass Filter

The simplest method, which eliminates problems with initial conditions and dc drift, which appear in pure integrator, is a method with low-pass filter. In this case the equation can be transformed as follows:

$$\frac{d\Psi_s}{dt} = (\bar{U}_s - R_s I_s) - \frac{1}{T_F}\Psi_s \quad (10)$$

The block diagram of the method with low-pass filter is presented in figure 5.

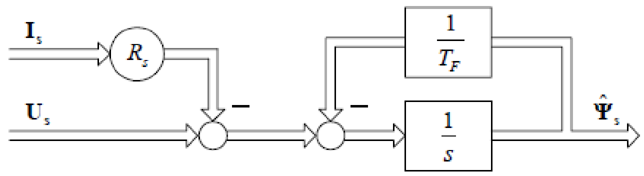

Figure 5. Flux Estimator based on voltage model with low-pass filter

The estimator stabilization time depends on the low-pass filter time constant T_F. Obviously, the low-pass filter produces some errors in phase angle and a magnitude of stator flux, especially when the motor frequency is lower than the cutoff frequency of the filter [2].

3. MODELING OF SVM-DTC

Initially, an algorithm is designed and simulated at the system level with the floating-point Simulink blocksets.A hardware representation for FPGA implementation is then derived using Xilinx System Generator (XSG), a plug-in tool to the Simulink modeling software [16]. The XSG provides a bit-accurate model of FPGA circuits and automatically generates a synthesizable VHDL code for implementation in Xilinx FPGAs. For DTC-SVM modeling, the blocks used are mostly multipliers, adders, MACs, etc.

The detailed steps are shown in the following diagram in figure 6. The first step is to determine the parameters of the power electronic section and use them to create a model using the PSB blocks. Also the hardware section of the prototyping board like the ADC can be simulated with a mathematical model. In this way, the control algorithm will be simulated as an exact replica of the real system. The next step is the building of the control algorithm with the use of only Xilinx System Generator blocks [17-19].

The next step is the simulation of the complete system in Simulink and VHDL code generation which is done with the “Xilinx System Generator” block. The process is totally automatic except the choice of the FPGA model required. Normally, the FPGA contains some other functions in addition to the algorithm. Therefore the algorithm must be connected to the remainder of the VHDL code.

3.1 Design of SVPWM Module

The Xilinx block configuration that produced the space vector modulation for this controller is presented in figure 7(a).The input magnitude and theta value that was converted into a binary value was sent into a sample and hold block as shown in figure 7(b), that was then sent into a Mcode block that selects the appropriate sector of the space vector modulation hexagon.

3.2 Design of Torque and Flux Estimation module

The XSG and Matlab/Simulink design of torque and flux estimator module and its submodules of DTC-SVM with low pass filter are shown in figure 8(a)-(d).

3.3 Design of PI Controller Module

PI controller is modeled using Xilinx System Generator as shown in Figure 9 .Very complex designs can be made easily with graphical algorithm approach by using the Xilinx system Generator in Matlab/Simulink environment.

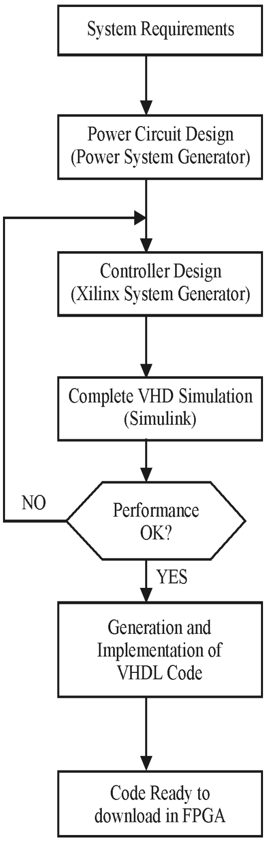

Figure 6. Induction Motor Drive Controller Design and Implementation Process

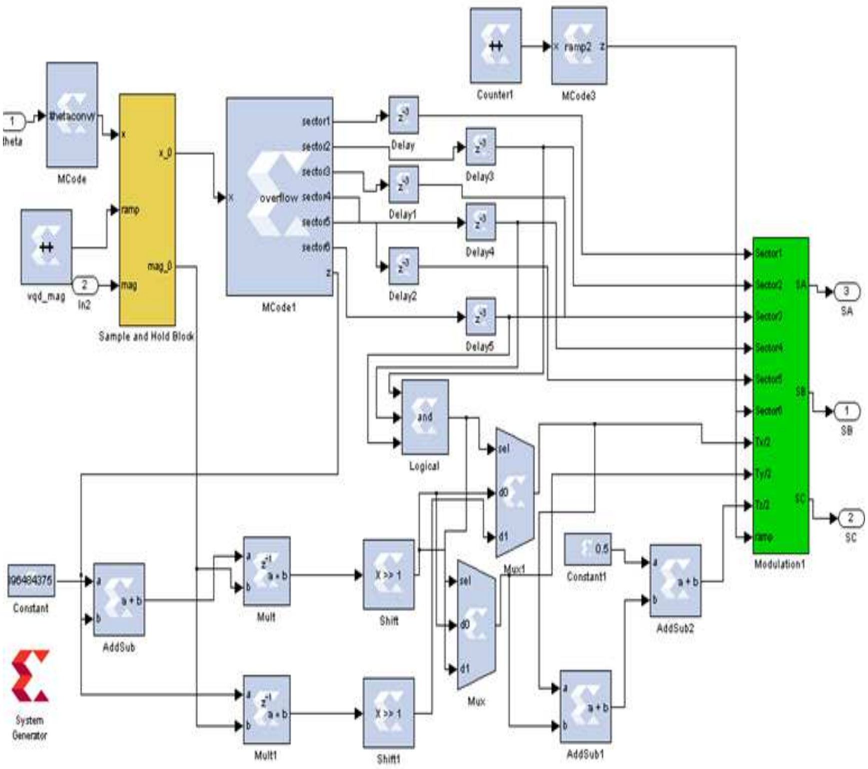

Figure 7(a). Xilinx Model of SVPWM

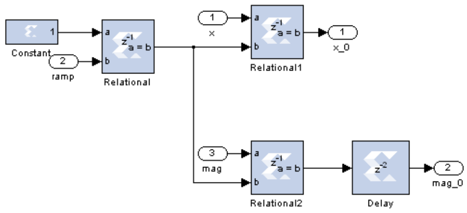

Figure 7(b). Sample and Hold subsystem

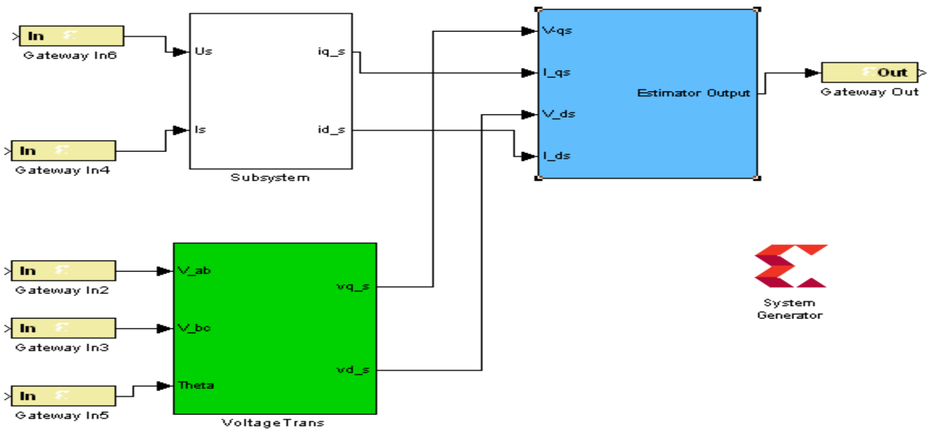

Figure 8(a). XSG and Matlab/Simulink model of torque and flux estimator

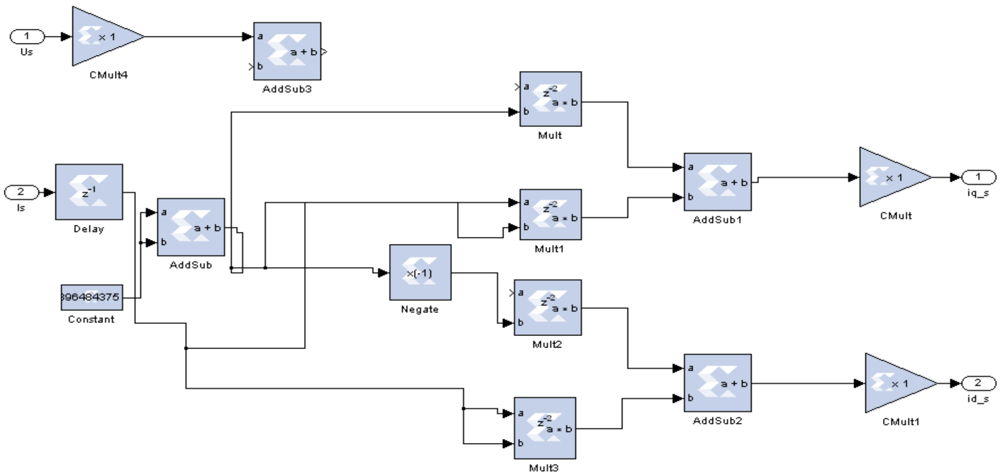

Figure 8(b).Modeling of Current Transformation Subsystem with XSG

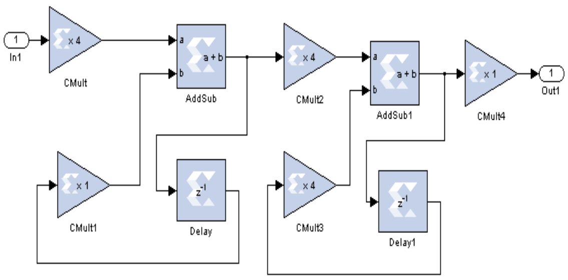

Figure 8(c).Modeling of Voltage Transformation Subsystem with XSG

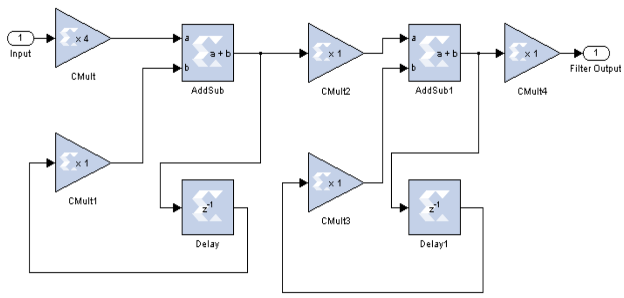

Figure 8(d) Modeling of Low Pass Filter

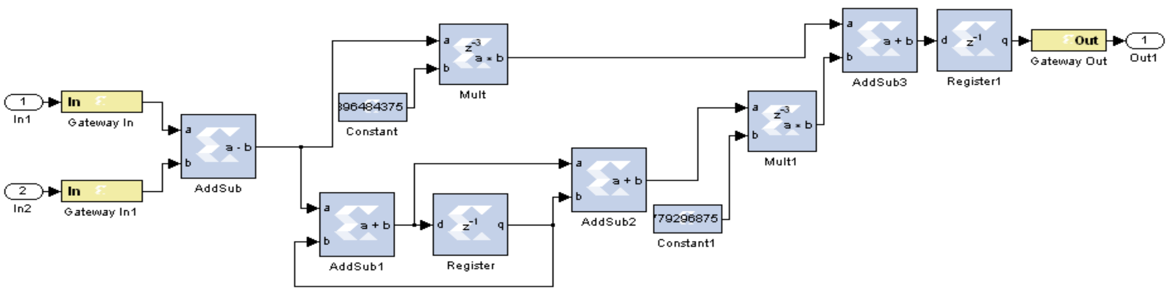

Figure 9. XSG model of PI controller

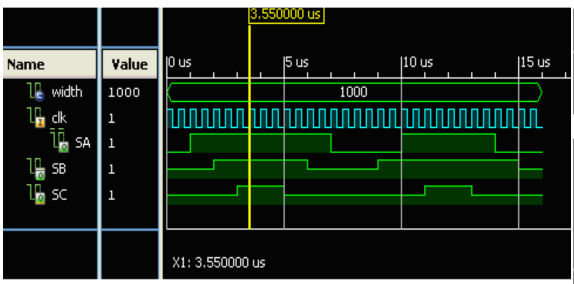

Figure 10(a) XSG Simulation of SVPWM(Sector I & II)

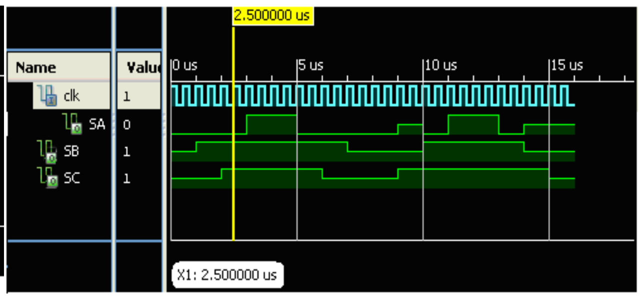

Figure 10(b) XSG Simulation of SVPWM (Sector III & IV)

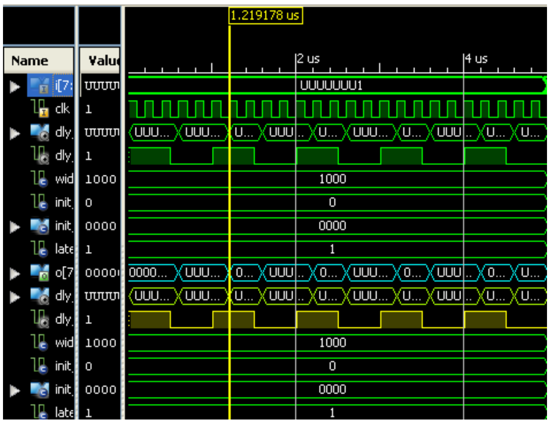

Figure 10(C) KSG simulation of torque and flux estimator with low pass filter

4. FPGA SIMULATION RESULTS OF SVM-DTC

The SVPWM based DTC for induction motor is simulated using XSG and Matlab/Simulink and the switching patterns at various sectors of SVPWM are shown in figure 10(a)-(b), simulation of torque and flux estimator with low pass filter and simulation of PI controller is shown in figure 10(c).

4.1. Synthesis and Implementation Results

The above designed model is synthesied using inbilt Xilinx Synthesis Tool (XST) and the implementation process is done using Xilinx PlanAhead software. The simulation of FPGA internal structure and I/O pins are as shown in Figure11(a) &(b).

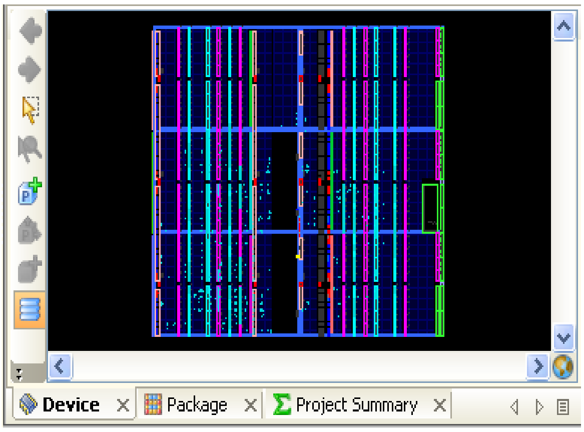

Figure 11(a) Internal structure of FPGA

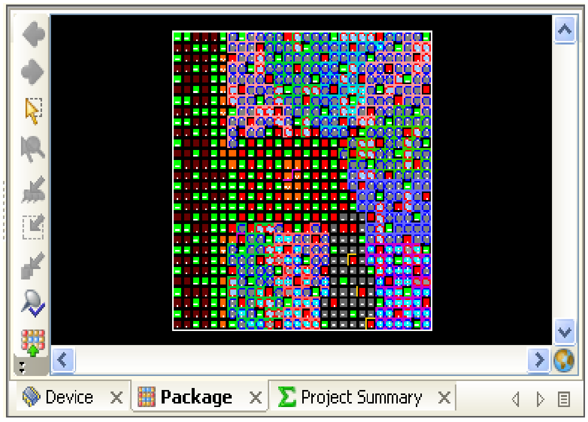

Figure 11(b) I/O structure of FPGA

5. CONCLUSIONS

The disgn and simulation of dynamically reconfigurable control struture for three phase induction motor drives was devloped in this paper. The high perfromance DTC-SVM with low pass filter overcomes the drawbacks of conventioanl DTC such as variable switching frequency, torque and flux ripples and current distotions.The proposed concept is simulated ans also the results are presented.

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