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Design, Test and Implementation of a single piston rotary valve Engine Control Unit

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Abstract: A prototype rotary valve engine has been built from a conventional single piston generator. In this study, an **e**ngine **c**ontrol **u**nit, ECU, is designed, tested and implemented for the purpose of carrying out the primary engine functions of sparking, fuelling and valve events control. The rotary valve engine has no camshaft, therefore, only a crankshaft (optical) sensor is required. The controller has also the advantage of turning the engine in either direction, removing the need for a reverse gear. Full control over valve events, together with crank motion independent sparking, removes the need for a throttle valve and a mechanical starter. With the valve turning freely, no feedback sensing is necessary. The proposed ECU has been designed, successfully tested and implemented on ALTERA's UP1 prototyping board. The FPGA programmable device used is the EPM7064SLC44-5.

Keywords: ECU, valve events. crankshaft, camshaft.

1. INTRODUCTION

In a conventional engine, the opening and closing of valves, called valve events, is controlled by a camshaft which is driven by a crankshaft via timing belt/chain, as shown in figure 1, (Gupta, 1988). Such systems have been known to suffer from timing problems and valve event control. For instance, if a timing belt/chain fails, valves may collide with pistons, causing destruction, (Mechadyne, 2007). Variable Valve Timing, VVT techniques can be incorporated into the camshaft system to make it vary the valve events in response to the change in engine speed and throttle demand, (Zibani *et al.* 2011a, b). However, VVT can be complex, expensive and cannot alter valve events for the entire engine speed, (Saied *et al*, 2006).

Electro-magnetic valve actuators, EMVA, can also be used to control valve events, (Liu *et al*, 2008). They can change the phasing and duration of valve events for all engine speeds and load conditions, to deliver better fuel economy, more power and less pollution. Although they are the most reliable type of actuators in terms of reaction time and reliability, EMVA systems have their limitations which includes valve chattering noise due to high sitting velocities, high power consumption, limited packaging space, complex valve position tracking algorithm, (Lancefield, 2007), (Kim, 2007).

The prototype rotary valve engine presented in (Zibani, *et al* 2011a), is a type of a camless EMVA system. The **e**lectronically **c**ontrolled **r**otary **v**alve, (**ECRV**), as it is known, offers several advantages over conventional EMVA systems. The motion of the valves is perpendicular to that of the pistons; therefore no valve-piston collision is possible. The system is open loop, therefore feedback algorithms are not required. The ECRV offers a fully flexible valve event control through software, removing the need for a throttle valve.

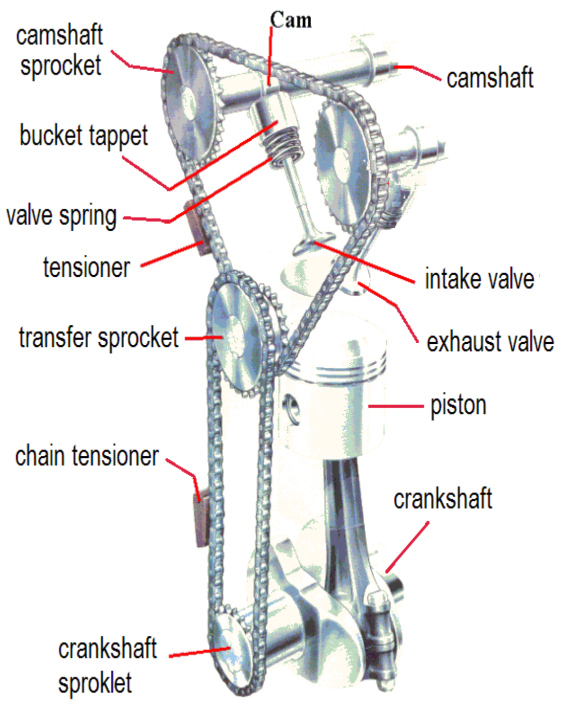

Fig. 1. Conventional Poppet valve system

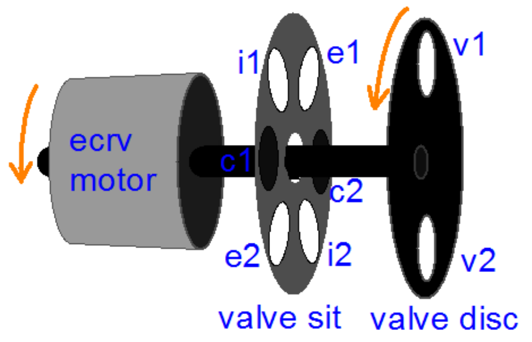

Fig. 2. The ECRV system model.

i1,i2 – intake channels; e1,e2 – exhaust channels

c1,c2 – closed channels; v1, v2 – valve opennings

The ECRV design got its motivation from the ancient rotary valve engine design schemes which now are only known as patents, (Wilson, 2002). Such design includes Aspin rotary valve and Cross rotary valve engine of the early twentieth century. (http, douglas-self.com). Coates also introduced a spherical rotary valve engine, (http, thetruthaboutcars.com). These designs mainly suffer from sealing problems as the compression and power stroke forces push the rotating assembly away from the sealing surface. Large 'sealing' forces applied on a moving valve may lead to excessive friction ans seizure.

As with the poppet valve, the engine's compression and combustion forces act on the **ECRV** in a way which just closes it tighter. The ECRV moves in between strokes, when pressure forces are at their minimum. As a result, frictional forces on the **ECRV** are reduced.

A conventional engines uses powertrain control module, PCM, to fire the cylinders. It uses two sensors; the camshaft position sensor, CMP, and the crankshaft position sensor, CKP, to synchronize the piston position with the ignition system, and also to obtain the engine revolutions per minute, RPM. For the ECRV system, only one crankshaft sensor, called piston direction sensor, PDS, is used. This results in a simplified design, which is detailed in the next section.

2. DESIGN OF THE ENGINE CONTROL UNIT

The rotary valve sketched in figure 2 demonstrates how the two engine Otto cycles shown in the flowchart of figure 3a match one cycle of the ECRV motor. During the first Otto cycle, the valve opening v1, exposes the cylinder to e1(exh1), i1(int1).and c1(cmpr1+pwr1). At the same time, v2 exposes the same cylinder to e2, i2 and c2. At the end of this cycle, the ECRV motor would have moved 180^0. During the second Otto cycle, v1 exposes the cylinder to e2, i2 and c2 while v2 exposes the same cylinder to e1, i1 and c1. For the two Otto cycles, the crankshaft would have moved four revolutions for a single revolution of the ECRV motor, considerably reducing valve wear. A camshaft would have done 2 revolutions. Note that exhaust channels e1&e2 are combined in the cylinderhead. So are input channels i1&i2, and closed channels c1&c2.

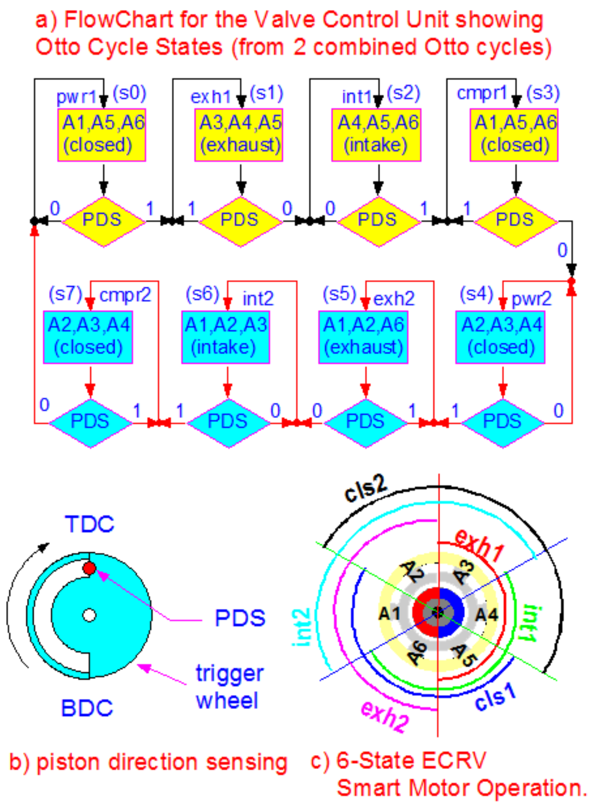

Fig. 3. Control of the Valve Events

2.1 Control of Valve Events

The combined Otto cycles of figure 3a yield 8 states. During the power and compression strokes, the valves remain closed. This is labelled as a single state, c, as far as the valve is concerned. Hence the valve disc in figure 2 goes through 6 states labelled e1, i1, c1, e2, i2, c2. The six state motor of figure 3c is used to operate the valve disc, (Zibani *et al* 2013).

The value of PDS controls the transition from one Otto cycle state to the next. During the exhaust and compression strokes, the piston moves up and PDS=1. During power and intake strokes, the piston moves down and PDS=0. If for example, when we are in state s0, we expect PDS=0, otherwise we stay in state s0 until it is so. This is correction of timing after a timing loss due to removal of car battery, for instance.

In figure 3c, A1 to A6 refers to the coils of the six state motor. For example, during exh1 (or e1), coils A3,A4,A5 are positively energised whilst coils A1,A2,A6 are negatively energised. Thus $e1 = \overline{A1}.\overline{A2}.A3.A4.A5.\overline{A6}$ $=001110_2$ $=0E_H$. The rest of equations for the states of the rotary valve can be derived in the same way.

The flowchart of figure 3a forms part of the engine control unit (called **e**ngine **f**ull **c**ontrol **m**odule, EFCM) which also handles fuelling and sparking. The truth table of the EFCM, shown in table 1, describes the functionality of the EFCM. The simulation results of the EFCM are shown in figure 4. The EFCM is further discussed in section 2.2.

PS	PDS,	stratified,	open,	dwell	NS	A,	F, S
S0 (PWR 1)	0,	0,	0,	0/1	S0	23,	0,0/1
	0,	0,	1,	0/1		07,	1,0/1
	0,	1,	0,	0/1		23,	0,0/1
	0,	1,	1,	0/1		07,	1,0/1
	1,	0,	0,	0/1	S1	23,	0,0/1
	1,	0,	1,	0/1		07,	1,0/1
	1,	1,	0,	0/1		23,	0,0/1
	1,	1,	1,	0/1		07,	1,0/1
S1 (EXH 1)	0,	0,	0,	0/1	S2	0E,	0,1/1
	0,	0,	1,	0/1		0E,	0,1/1
	0,	1,	0,	0/1		0E,	0,1/1
	0,	1,	1,	0/1		0E,	0,1/1
	1,	0,	0,	0/1	S1	0E,	0,1/1
	1,	0,	1,	0/1		0E,	0,1/1
	1,	1,	0,	0/1		0E,	0,1/1
	1,	1,	1,	0/1		0E,	0,1/1
S2 (INT 1)	0,	0,	0,	0/1	S2	07,	1,1/1
	0,	0,	1,	0/1		07,	1,1/1
	0,	1,	0,	0/1		07,	0,0/0
	0,	1,	1,	0/1		07,	0,0/0
	1,	0,	0,	0/1	S3	07,	1,1/1
	1,	0,	1,	0/1		07,	1,1/1
	1,	1,	0,	0/1		07,	0,0/0
	1,	1,	1,	0/1		07,	0,0/0
S3 (CMPR 1)	0,	0,	0,	0/1	S4	23,	0,1/1
	0,	0,	1,	0/1		23,	0,1/1
	0,	1,	0,	0/1		23,	1,1/1
	0,	1,	1,	0/1		23,	1,1/1
	1,	0,	0,	0/1	S3	23,	0,1/1
	1,	0,	1,	0/1		23,	0,1/1
	1,	1,	0,	0/1		23,	1,1/1
	1,	1,	1,	0/1		23,	1,1/1

PS	PDS,	stratified,	open,	dwell	NS	A,	F, S
S4 (PWR 2)	0,	0,	0,	0/1	S4	1C,	0,0/1
	0,	0,	1,	0/1		38,	1,0/1
	0,	1,	0,	0/1		1C,	0,0/1
	0,	1,	1,	0/1		38,	1,0/1
	1,	0,	0,	0/1	S5	1C,	0,0/1
	1,	0,	1,	0/1		38,	1,0/1
	1,	1,	0,	0/1		1C,	0,0/1
	1,	1,	1,	0/1		38,	1,0/1
S5 (EXH 2)	0,	0,	0,	0/1	S6	31,	0,1/1
	0,	0,	1,	0/1		31,	0,1/1
	0,	1,	0,	0/1		31,	0,1/1
	0,	1,	1,	0/1		31,	0,1/1
	1,	0,	0,	0/1	S5	31,	0,1/1
	1,	0,	1,	0/1		31,	0,1/1
	1,	1,	0,	0/1		31,	0,1/1
	1,	1,	1,	0/1		31,	0,1/1
S6 (INT 2)	0,	0,	0,	0/1	S6	38,	1,1/1
	0,	0,	1,	0/1		38,	1,1/1
	0,	1,	0,	0/1		38,	0,0/0
	0,	1,	1,	0/1		38,	0,0/0
	1,	0,	0,	0/1	S7	38,	1,1/1
	1,	0,	1,	0/1		38,	1,1/1
	1,	1,	0,	0/1		38,	0,0/0
	1,	1,	1,	0/1		38,	0,0/0
S7 (CMPR 2)	0,	0,	0,	0/1	S0	1C,	0,1/1
	0,	0,	1,	0/1		1C,	0,1/1
	0,	1,	0,	0/1		1C,	1,1/1
	0,	1,	1,	0/1		1C,	1,1/1
	1,	0,	0,	0/1	S7	1C,	0,1/1
	1,	0,	1,	0/1		1C,	0,1/1
	1,	1,	0,	0/1		1C,	1,1/1
	1,	1,	1,	0/1		1C,	1,1/1

Table 1: Truth Table for efcm

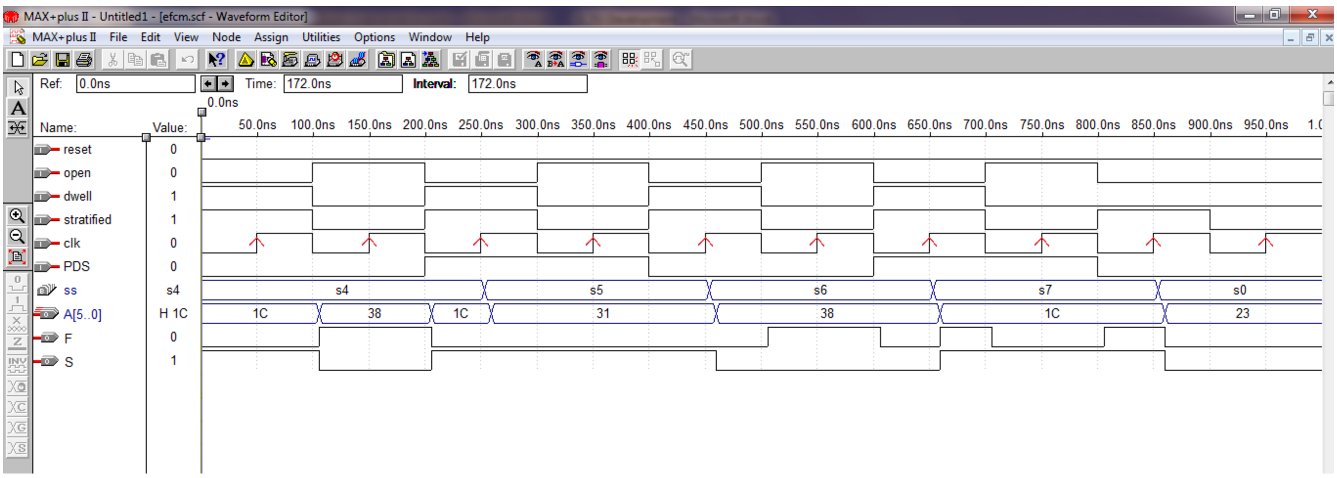

Figure 4. Simulation Results for EFCM

2.2 Engine full control module, EFCM

The EFCM generates coil outputs, A, the fuel injector output, F and the spark plug output, S. The input, stratified allows the EFCM to operate the injector in the compression stroke (rather than the usual intake stroke) for improved efficiency. The inputs open and dwell from the start-stop system allows the EFCM to start the engine electronically without using a mechanical starter, (Zibani *et al*, 2013).

The waveform output of figure 4 confirms the flowchart of figure 3a. An active high clock input (shown with red arrows) is used. For example, from 0.0ns to 200.0ns, PDS = 0. So when a positive going clock edge pulse is delivered at 150.0ns, we remain in state s4. At 250.0ns, we progress to s5, in agreement with the flowchart of figure 3a. At 350.0ns, we remain in s5 since PDS=1 at this time, and S=1, F=0 and $A=31_H$, as suggested by the truth table of table 1. Analyzing the rest of the waveforms of figure 4 will show that they are in agreement with the truth table and flowchart of EFCM.

2.3 The ECRV control system

Figure 5 shows the interaction between the EFCM and other modules. The EFCM uses the PDS signal to move from one state to the next. A pulse transition detector generates an event clock needed to drive the EFCM. The electronic start – stop module allows the engine to start electronically not using a starter motor (Liu *et al*, 2011). The stop system cuts off the fuel to stop the engine. The activity sensor deactivates the stop system and the direction changer when the engine is running. The stratified input allows the EFCM to inject fuel during the compression stroke (rather than the usual intake stroke) for improved efficiency.

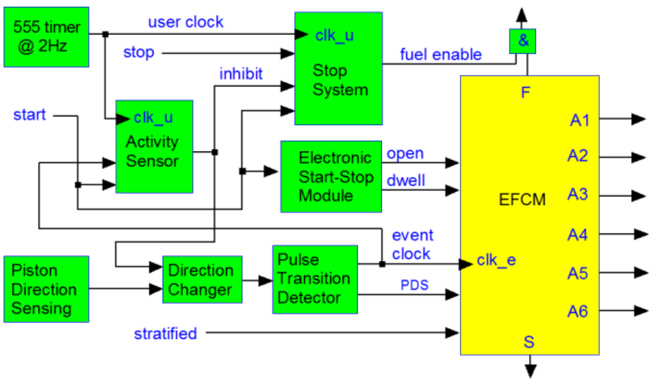

Fig. 5. Block diagram of ECRV control system

The outputs of the EFCM are connected to output drivers F (fuel injector driver), S (spark plug driver), Ai (motor coil drivers). The motor coil drivers of figure 6a) consists of two pairs of npn-pnp power transistors connected back to back to achieve the push-pull function required to operate each coil.

In a similar way, the fuel injector and spark plug drivers (figure 6c) consist of power transistors which handle high currents.

The slide/press op-amp switch of figure 6b) is ideal for the START, STOP or STRATIFIED inputs design to the ECRV system.

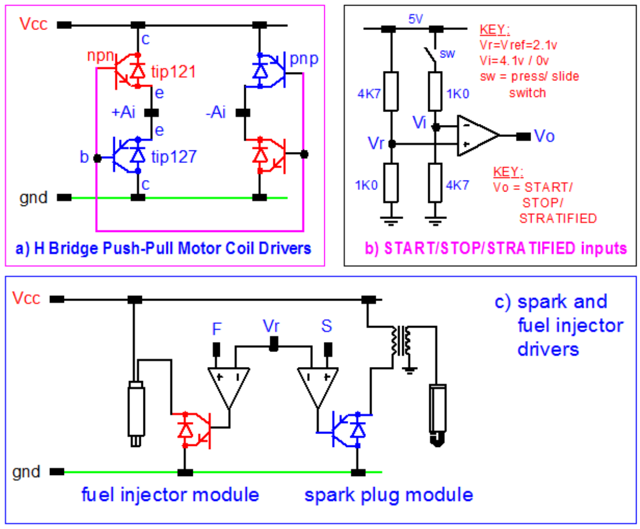

Fig. 6. Various input and output drivers

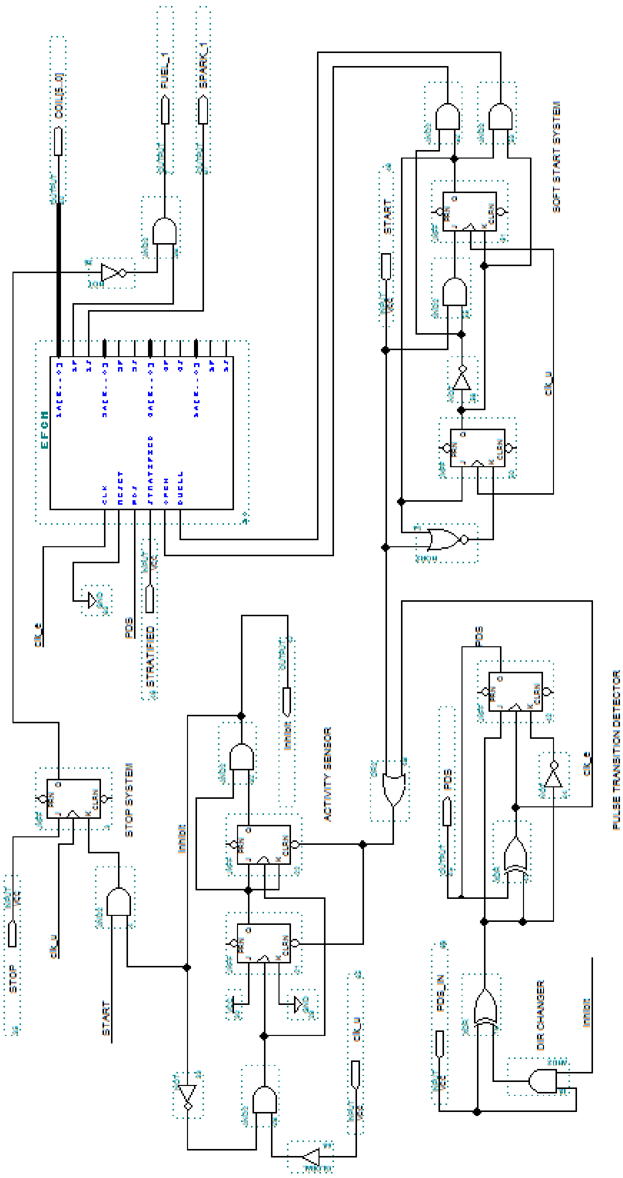

Fig. 7. The Max plus II Design Project of the digital aspect of ECRV

2.4 The ECRV system design using max plus II

The block diagram of figure 5 shows the peripheral inputs to the EFCM. ALTERA's max plus II development software was used to design, test and implement the ECRV system. The max plus II ECRV graphical design project (figure 7) shows how EFCM is connected to it's control logic. The EFCM itself was designed using ALTERA's AHDL text editor which can be represented by an 'easy-to-read' truth table given in table 1. The design project was then compiled with max plus II compiler to produce programming files. The compilation process is shown in figure 8, (Altera Corporation, 2006).

The Timing Compilation Process consists of the Compiler Netlist Extractor and Database Builder which build netlist database and check for syntax errors. The Logic Synthesizer performs logic synthesis/minimization, the Design Doctor checks for design violations, the Partitioner and Fitter executes place & route algorithm and builds the .rpt file on device implementation. The Timing SNF Extractor builds .snf file for simulation and timing analysis, and finally the Assembler builds files for programming the device.

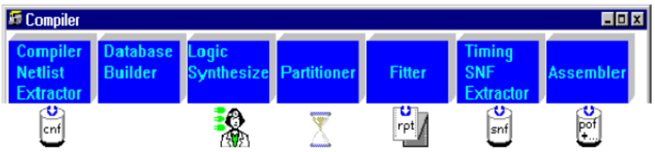

Figure 8. Max plus II Compilation Process

2.5 Device programming

Programming the target device was done using a USB download cable (Figure 9), programming software and UP1 prototyping board (figure 10).

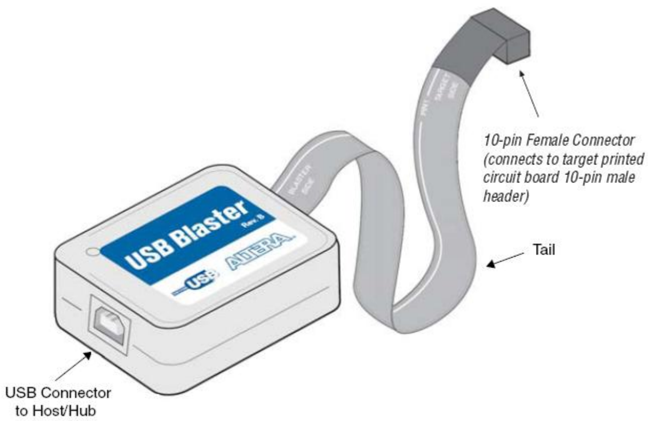

Fig. 9. USB Blaster download cable

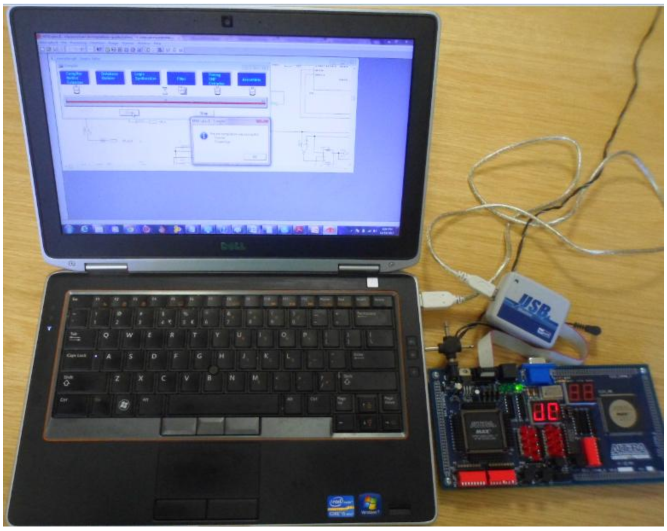

Fig. 10. JTAG Device programming using UP1 prototype board and USB Blaster download cable.

2.6 PCB Board Design

The PCB board given in figure 11 was designed using QuickRoute PCB design software. The design project given in figure 7 represents the digital aspect of the ECRV control system, which was programmed into the EPM7064SLC44-5. The outline of this device is visible on the PCB design shown in figure 11. The various analog devices (555 timer circuit, all driver modules) are not programmable and hence appear as they are on the PCB board. The various components and modules are well labelled. However for the final PCB board, all device labels and their outlines are omitted and the remaining tracks are mirrored and printed to the board.

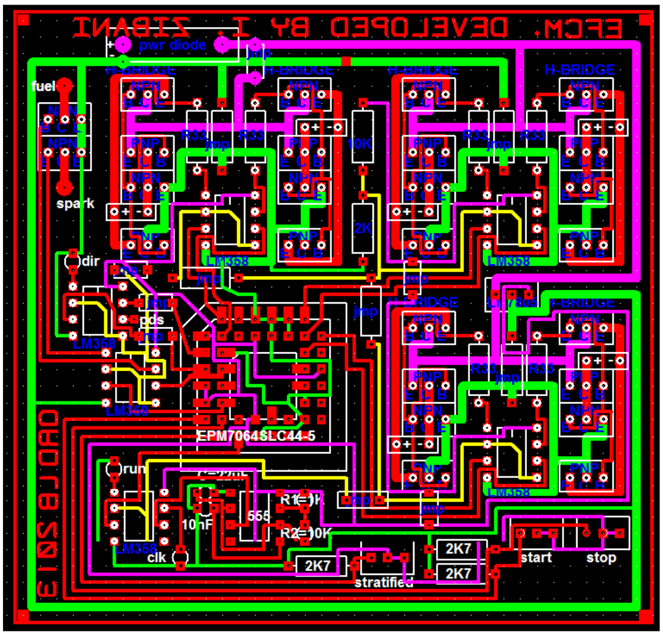

Fig. 11. PCB Board Design

3. CONCLUSIONS AND FUTURE DIRECTIONS

The EFCM was successfully designed, tested and modelled. The successful performance of the EFCM means that we can extend this concept to a 4 piston engine controller. Benefits such as electronic start stop, and bi-directional engine rotation can be archived, (Zibani *et al* 2013). The flexibility of valve event control using EFCM means that the ECRV engine can easily satisfy emissions international regulations, resulting in a smoother, more efficient, powerful and environmental friendly engine. Because of its reliability and safe operation, the ECRV concept can be extended to more sensitive industrial applications like aircraft engines.

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