

15th Global Conference on Sustainable Manufacturing

Control Unit for a Coreless Stator for use with SI Engine Stepping Valve.

I. Zibani^a, R. Marumo^b, J. Chuma^c, I. Ngebani^d and K. Tsamaase^{e,*}

^{a,b,e,d}University of Botswana, P/Bag 0022, Gaborone, Botswana

^cBotswana International University of Science and Technology, P/Bag 16, Palapye, Botswana

Abstract

Engine efficiency could be increased if valve timing could change with engine revolutions per minute. Poppet valves are fitted with strong springs which return them to their rest positions after being pushed down by cam lobes. Overcoming the spring loaded camshaft drive train requires a lot of engine power. Valve lift, lift duration and phase cannot be adapted with cam lobes on the camshaft but electromagnetic actuators or hydraulic/pneumatic phasing mechanisms could achieve change of lift duration and phase change. Stepping valves with flexible valve event software control, move perpendicular to the piston, thus avoiding piston valve collision problem. Engine cranking requiring fuel, spark and valve event can be done electronically without engine turning. The design of a control unit for an axial coreless stator to control the motion of the stepping valve through the Otto cycle positions intake, exhaust and power / compression is presented with successful simulation of the control algorithm. A 3phase, 12V coil prototype stator with 4 coils per phase, connected in series and consuming 3A from a 12V car battery has been prototypically realized. The project aims at essential processes to run the engine as fuel, air, spark all being software controlled, leading to a more efficient, environmentally friendly, reliable and powerful engine.

© 2018 The Authors. Published by Elsevier B.V.

Peer-review under responsibility of the scientific committee of the 15th Global Conference on Sustainable Manufacturing (GCSM).

Keywords: Stepping Valve, Valve Events, Axial Coreless Stator, Control Unit.

* Corresponding author. Tel.: +267-355-4443; fax: +267-395-2309.

E-mail address: zibani@mopipi.ub.bw

1. Introduction

The performance of a spark ignited (SI) internal combustion (IC) engine is dictated by the valve events [1, 2, 3]. For the modern car, the admission of the spark, and fuel into the combustion chamber is electronically controlled. However the movement of air in and out of the combustion chamber is difficult to regulate as this is done mechanically. The proposed stepping valve can offer unparalleled engine performance for the entire engine speed [4].

1.1. Conventional poppet valve system

The conventional camshaft system primarily consists of poppet valves housed in a cylinder-head. The valve events are mechanically controlled by a spring loaded camshaft. In turn, the camshaft is controlled by the crankshaft [5, 6]. Therefore, for the valves to open or close, the crankshaft must be turning. When the poppet valves open or close, they physically move up and down the combustion chamber, against the motion of the pistons. Should the valve timing fail, the valve could be driven into the incoming piston, resulting in a physical damage to the engine. Furthermore, the timing of the valve events is engraved on the cam lobes of the camshaft, therefore, can't be changed. However, for an engine to be efficient, the valve timing should change with engine *revolutions per minute*, RPM. During manufacture, the timing has been set to the mid RPM range, which is used mostly. That means, for other RPM ranges, the engine efficiency is compromised, [7, 8].

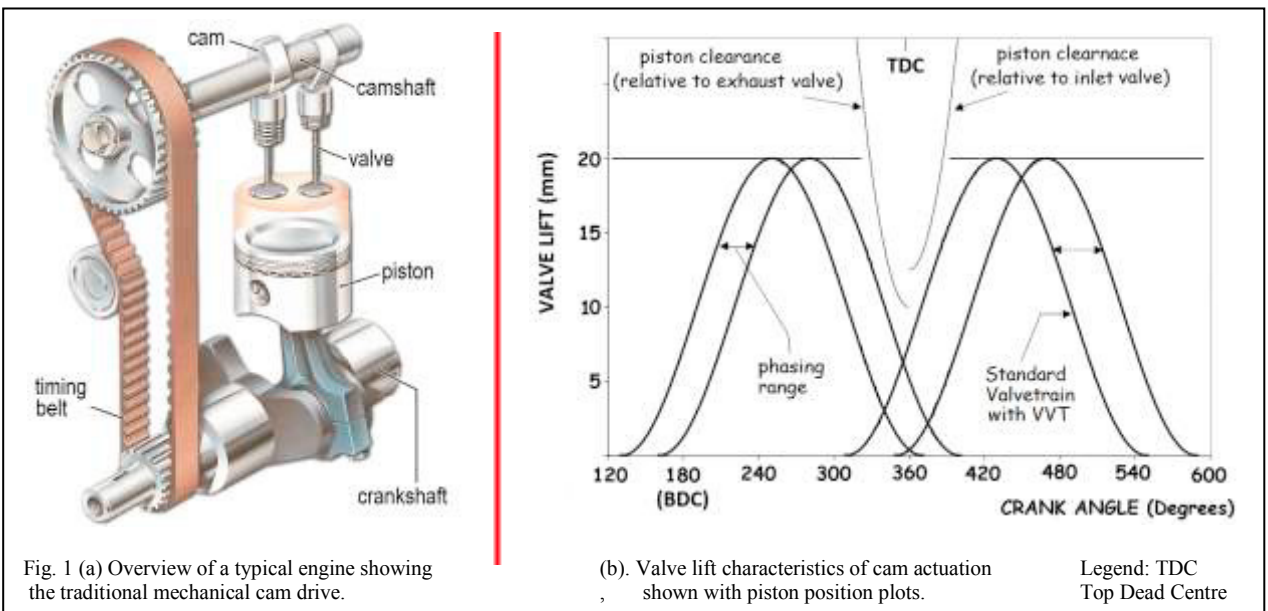


Figure 1(a) shows how the camshaft is timed to the crankshaft using a timing belt. Figure 1(b) shows that the piston will be at top dead centre, TDC at a crank angle of 360° . At this point, valve lift is restricted to 10mm to avoid collision with the piston. Poppet valves are fitted with strong springs which return them to their rest positions after being pushed down by the cam lobes [9, 10, 11]. A lot of engine power is required to overcome this spring loaded camshaft drive train. The cam lobes are instilled onto the camshaft, which makes it impossible to adjust valve lift, lift duration and phase. However, by using some form of electromagnetic actuators or hydraulic/pneumatic phasing mechanisms, some degree of lift duration and phase change can be achieved [12,13,14].

1.2. The stepping rotary valve system

In our previous work [4], we demonstrated that the performance of a stepping valve outweighs that of a conventional poppet valve. An earlier version of the stepping valve is shown in figure 2. The valve moves perpendicularly to the piston, therefore avoiding the inherent piston-valve collision problem. Due to the fact that the stepping valve motion is perpendicular to that of the piston, the valve events can occur even if the engine is not running. That means the valve events can be software tuned in response to any change in RPM, resulting in uniform engine efficiency. With the flexible valve event software control, and using the right accessories, an engine can be changed from 2- to 4-stroke.

In a conventional poppet valve system, the camshaft is mechanically driven by the engine crankshaft. Therefore for the valves to open or close, the engine must be turning. For the engine to crank (or start), the intake valve needs to open to admit air, the fuel injector needs to fire to admit fuel into the combustion chamber and finally a spark is required to ignite the fuel air mixture [7]. For the stepping valve system, the valve events can occur without the engine turning. So the three requirements needed for engine cranking (fuel, spark, valve event) can be done electronically without the engine turning. That means the mechanical starter won't be required in this case.

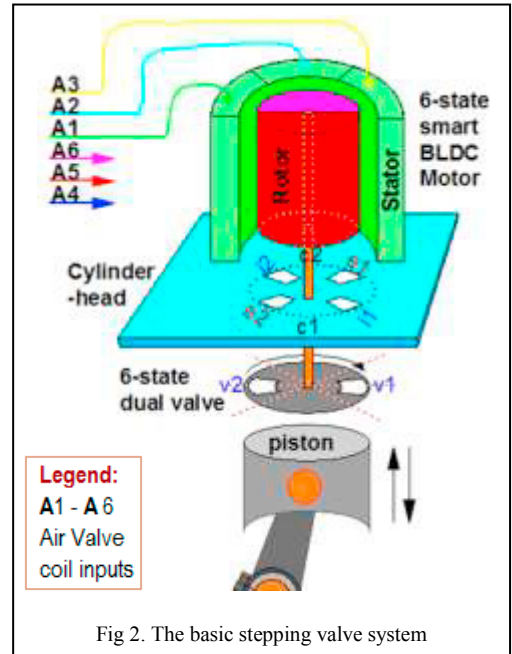


Fig 2. The basic stepping valve system

2. Design of the Control Unit for the stepping valve stator

In this study, we present the design of a control unit for an axial coreless stator. A coreless stator does not suffer from iron losses which results from Eddy current flow, [15]. The stepping valve goes through the 3 valve states; exhaust, intake and closed (figure 3a). To keep the valve stationary on its state, the stator current must be on. However, we can strategically place soft iron pieces on the periphery of the stator so that they can attract and keep the rotor in place once the stator current is turned off (figure 4a). Moving from the compression to the power stroke, the valve status (closed state) remains the same. As a result, the total power required for the valve events is saved. For a typical car travelling at 120km/hr, it registers a corresponding RPM of 2700. Put another way, each Otto cycle/state will take $\frac{1\text{min}}{2700\text{rev}} \cdot \frac{60\text{sec}}{1\text{min}} \cdot \frac{\text{rev}}{2\text{cycles}} = 11\text{ms}$. A stepping valve has 4 holes (figure 9), each one to serve the 4 Otto states/cycles [4]. With reference to the stepping valve, each Otto cycle time is given by;

$4 \text{ valve holes} \cdot \frac{4 \text{ Otto states}}{\text{valve hole}} \cdot \frac{11\text{ms}}{\text{Otto state}} = 176\text{ms}$. The corresponding measured response time (valve event time) for a 200Watts stepping valve system is 9ms. As a percentage, this is $\frac{9\text{ms}}{176\text{ms}} \cdot 100\% \approx 5\%$. That means for 2700RPM, the stator coil needs to be switched on for only 5% of the Otto cycle state time, saving power. Moving from compression to power stroke, the stator coils stay off, another power saving technique. A conventional poppet valve system will have camshaft Otto cycle time = 2*crank revolution time. The valve event here lasts for the entire camshaft Otto cycle time (see figure 1b). The stepping valve has a constant and much shorter valve event time, therefore giving gases more time to move in/out the combustion chamber. From the above analysis, the speed of the crankshaft is 8 times that of the stepping valve, therefore there is less wear on the stepping valve.

2.1. The Piston Direction Sensing

Figure 3a) shows the engine Otto cycle for a spark ignited internal combustion engine. In a conventional engine, the Otto cycle states are mechanically driven by the camshaft. The Otto cycle sequence is engraved on the cam lobes which then push down on the poppet valves in the right sequence. (See figure 1a). For the stepping valve system,

the Otto cycle sequence is event driven through **piston direction sensor** or PDS. The crankshaft trigger-wheel (or pulse-wheel) is just a single bit encoded disc which reads the direction of the piston motion. It can be attached to the crankshaft sprocket [16]. However, the timing belt drive pulley can also act as a pulse-wheel if encoded accordingly. The PDS is an optical sensor which can be placed where the crankshaft position sensor, CKP (or TDC sensor) is normally placed. Assuming that the engine turns clockwise, when the piston moves down, PDS produces logic 0 (as it is shielded from view) and when the piston moves up, PDS produces logic 1.

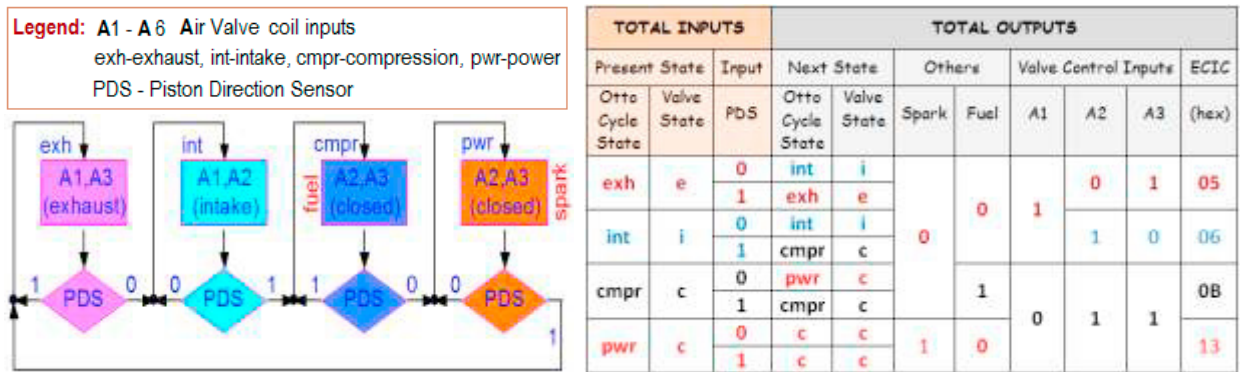


Fig. 3a) The Valve state and Otto cycle Flow Chart

b) The truth table for the Engine Control Unit

2.2. The Event Driven Otto Cycle

As the piston changes direction, PDS changes value. Furthermore, each time PDS changes value, a clock pulse called event clock is generated. Figure 3a shows the event driven Otto cycle. When PDS = 0, (i.e. piston moving down), we remain in the intake/power strokes. When PDS=1, (i.e. piston moving up), we remain in the exhaust/compression strokes. Figure 3b) shows the engine control unit (ecu) derived from the flow chart of figure 3a. When the engine starts, the piston could be, say moving down (intake/power), but the ecu will normally be in the reset state, in this case the exhaust state. During this time, the event-clock won't be available since the engine is not turning. So the starting process will generate a clock to drive the Otto cycle to the next state pair reflected by the stationary piston (intake/power). The intake stroke will be automatically chosen since it comes first. The timing is now achieved and the engine can start successfully. The Engine Control Inputs Code, (ECIC) shows the total state of the ecu. For example, if we are in the compression state, the outputs vector [spark,fuel,A1,A2,A3]=[10011]_{BIN} = [0B]_{HEX}. ECIC is used to initiate the main engine events.

2.3. The Design of the coreless axial actuator

Figure 4 shows the design of the axial stator and the pancake rotor. The stator shows 12 coils, A1→A12, arranged clockwise. There are three phases, labeled +A1, +A2 and +A3. There are 4 coils per phase wired in series as shown in figure 4. The three phases terminations are labeled -A1(A10), -A2(A11) and -A3(A12) respectively. For example, the phase set +A1 ↔ -A1 contains 4 coils, A1, A4, A7 & A10. A1, A2 and A3 will be referred to as fundamental coils. Secondary coils are connected in series to their corresponding fundamental coils. The purpose of the secondary coils is to ensure that the 12 pole rotor follows a 12 state rotation using only the 4 state Otto cycle of figure 3a. The coils are colour coded to reflect their magnetic orientation; red coil=positive energisation to produce a north pole, blue coil=south pole. Similarly, red magnet phase=north pole, blue magnet phase=south pole. According to figure 3a, the initial state of the valve is the exhaust state with the fundamental coils A1, A3=1 & A2=0. Figure 4 shows the stable exhaust state since coil A1 will attract RA1, A2 will attract RA2, and so on. For the next state, (intake), A1,A2,A3=1,1,0. This is like turning the colour coded stator one step clockwise (+30°), with the coil names remaining on the same spot. Since the magnetic field of the stator has moved one step clockwise, the rotor will follow suit. The rotor will initially be pushed away from the stator to 'un-sit' the valve, so that it moves to its next position without rubbing against its seat. After the valve has reached its correct phase alignment with the coil's new

magnetic field, it will be attracted back to the coil, thereby achieving initial valve sealing. The compression or power stroke will further reinforce the valve sealing to achieve a good power/compression stroke.

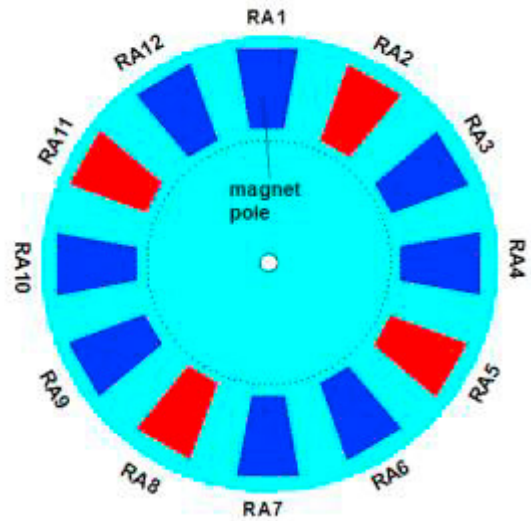
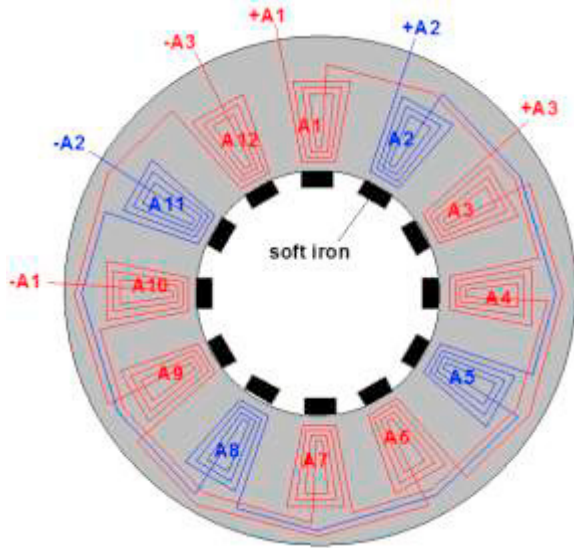


Fig. 4a). Axial Stator showing 3 phases with 4 coils per phase.
The coils are colour coded to show the initial valve state;
red=positively energised coil (logic1),
blue =negatively energised coil (logic 0).

b) Pancake Rotor. The pole magnets are
colour coded to show pole polarity:
red=north pole, blue=south pole

3. Simulation of the control unit

The schematic design of the ecu system is illustrated on figure 5. The pulse wheel rotates clockwise. As shown in the figure, the piston is at TDC. When it starts to move down (power/intake), the PDS optical sensor will be under the shadow of the disc so that it reads logic 0. When the piston moves upwards towards TDC (compression/exhaust), the circular cut out on the disc exposes the PDS sensor so that it reads logic 1. The Schmitt trigger captures these readings and delivers them to a Pulse Transition Detector, PTD which produces a clock pulse (event clock) for every event. The engine control unit processes the PDS signal information on every event clock.

The event clock signals the start/end of an Otto cycle state. To save power, it is desired to energise the H Bridge Drivers for a minimum time just to allow the system to move to the next Otto cycle state (section 2). This minimum time is programmed into the H Bridge Driver Enabler, which is basically a count-down counter that gets locked to its lowest value to disable the H Bridge Drivers. When we come to the next Otto state, the event clock will preset this counter, triggering it to start counting down again. The event signal registers will trigger the H Bridge Drivers to change their outputs in response to a change in the valve outputs A_i .

4. Simulation Results using ALTERA Development System

Figure 6 shows ALTERA Max Plus II schematic representation of figure 5. The text editor representation of the ecu simulator (ecu_compact) is given in figure 7. The waveform of figure 8 describes the behaviour of the circuit of figure 5. The event clock initialises all the engine activities. Figure 8 captured 4 valve events. At $t=8\mu\text{s}$, the first valve event occurs when PDS goes high. The *pulse transition detector*, PTD generates an event clock which drives the ECU system to the exhaust state designated by $\text{ECIC}=05_{\text{H}}$. The *HBridge driver enabler* (HBDE) is triggered at this point to start its down count process, with its BRIDGE output high to enable the H Drivers. At $8.6\mu\text{s}$, the HBDE has counted down to 0, and its BRIDGE output will become 0 to disable the H Drivers for the rest of the exhaust cycle. The next clock event occurs at $t=9.55\mu\text{s}$, triggering the ecu to go to the intake stroke with $\text{ECIC}=06_{\text{H}}$. Similarly, the HBDE counts down to 0 at $10.25\mu\text{s}$ and disabling the H Drivers at this point. The next clock events

occur at $t=11.5\mu\text{s}$ (compression stroke, $\text{ECIC}=0\text{B}_\text{H}$) and at $t=12.7\mu\text{s}$ (power stroke, $\text{ECIC}=13_\text{H}$). Whilst the H Bridge drivers are disabled, no current is delivered to the stator coils, thereby saving power. The results obtained are consistent with the truth table of figure 3b. The model of figure 9 correctly demonstrated the transition of Otto cycle states as depicted by the flow chart of figure 3a.

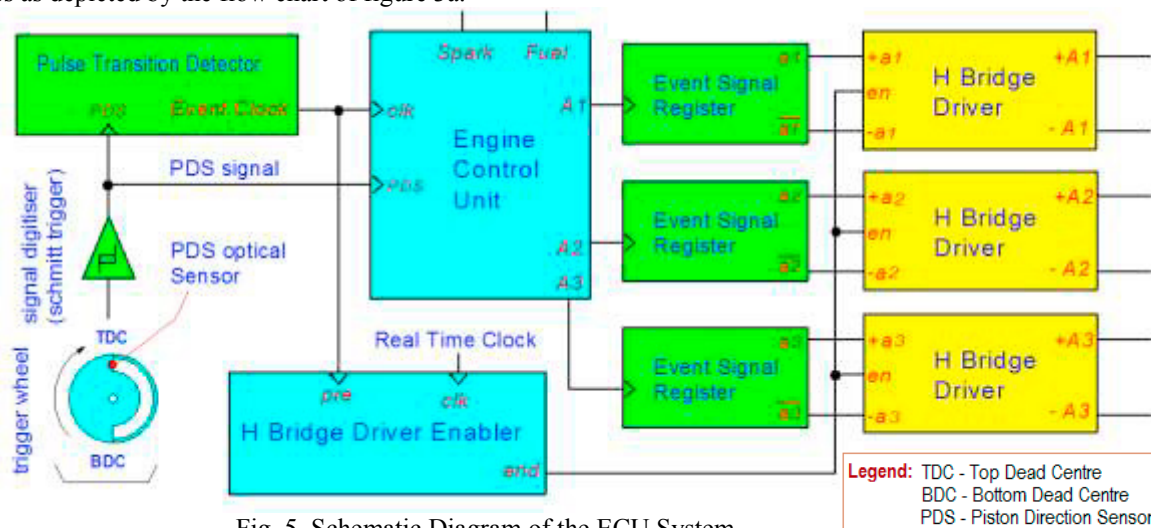


Fig. 5. Schematic Diagram of the ECU System

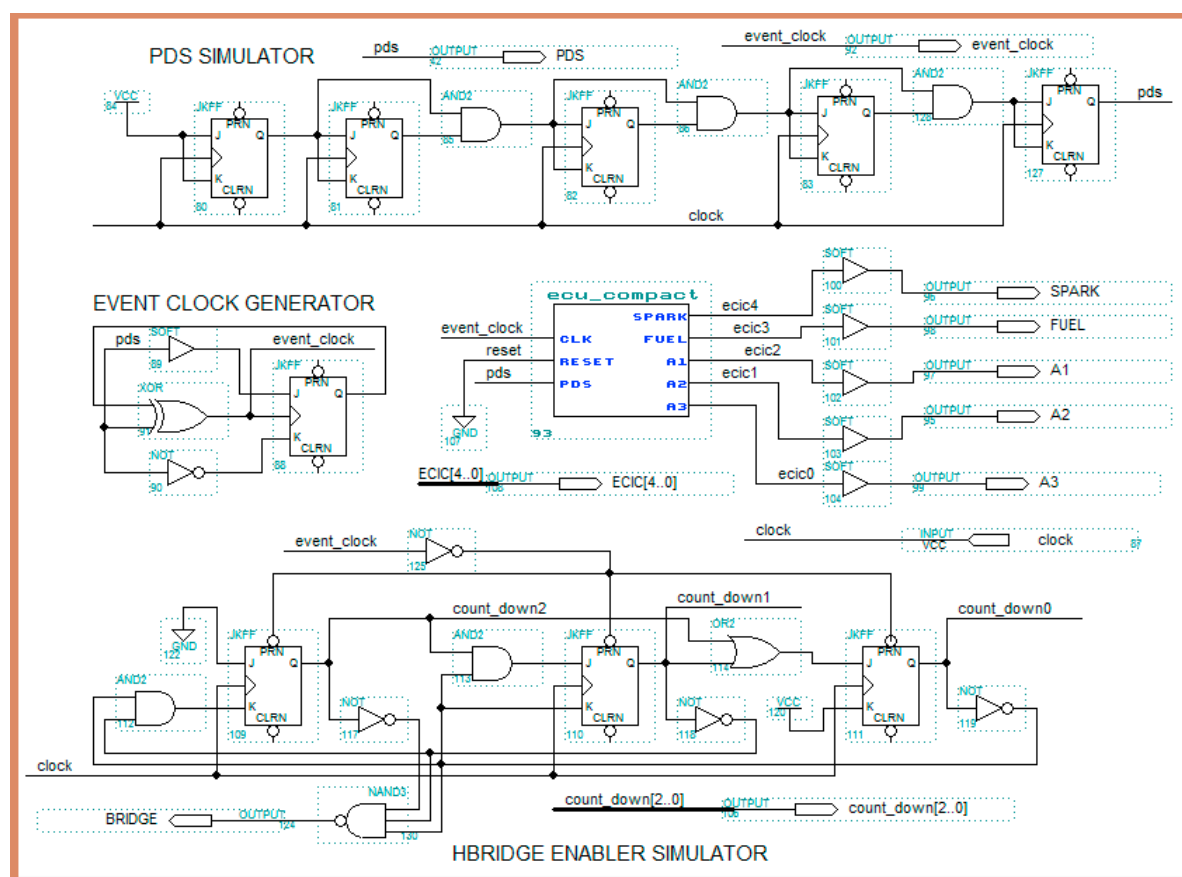


Fig. 6. ALTERA's Max Plus II Design of the ECU System

```

% the compact engine control unit %

SUBDESIGN ecu_compact
(
  clk, reset, pds :INPUT;

  Spark, Fuel, A1, A2, A3      :OUTPUT;
)
VARIABLE
ss:MACHINE WITH STATES(exhaust, intake, compression, power);
BEGIN
ss.clk=clk;
ss.reset=reset;

TABLE
% present
% state      input  output(s)      next %
% state
ss,
exhaust,    0 => 0, 0, 1, 0, 1,  ss;
exhaust,    1 => 0, 0, 1, 0, 1,  exhaust;

intake,     0 => 0, 0, 1, 1, 0,  intake;
intake,     1 => 0, 0, 1, 1, 0,  compression;

compression, 0 => 0, 1, 0, 1, 1,  power;
compression, 1 => 0, 1, 0, 1, 1,  compression;

power,      0 => 1, 0, 0, 0, 1, 1,  power;
power,      1 => 1, 0, 0, 0, 1, 1,  exhaust;

END TABLE;
END;

```

Fig. 7. Max Pluss II AHDL text editor of the ECU

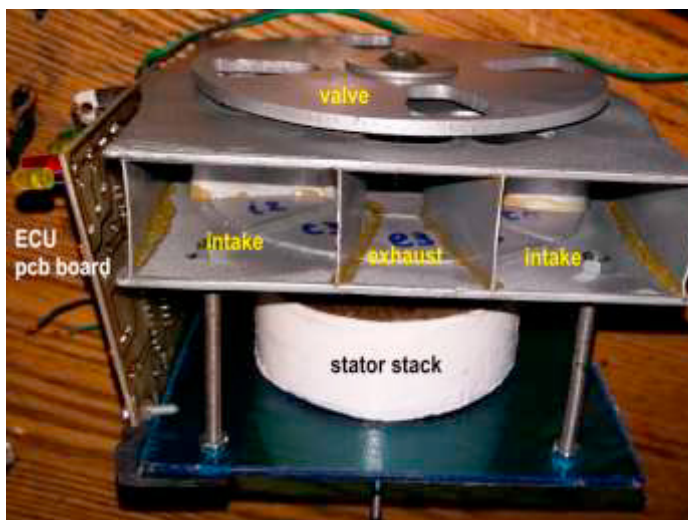


Fig. 9. Stepping Valve Model showing the ECU pcb board, intake/exhaust vents and the 4 holed valve.

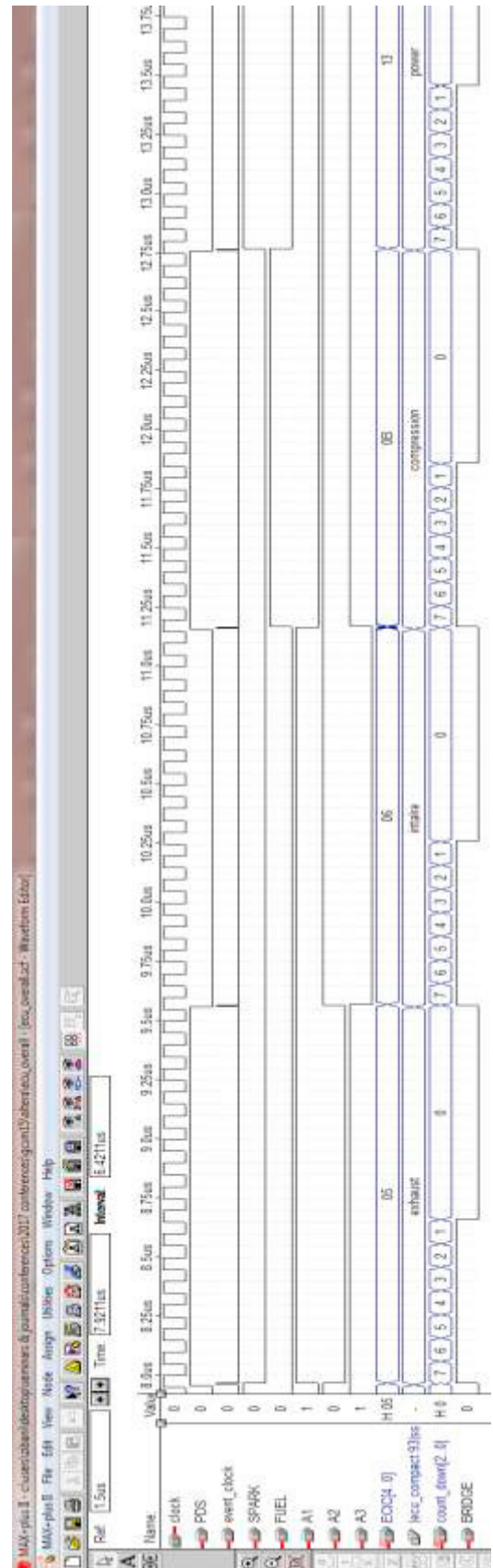


Fig. 8. Output Waveform of the ECU System of Fig. 6. →

Conclusions and further work

A successful simulation of the ECU system has been demonstrated using Altera's Max Plus II development tools. A demo stepping valve prototype (figure 10) was also setup to demonstrate the theoretical concepts of figure 5. As stated in section 1, the stepping valve system offers a number of advantages as compared to conventional poppet valve systems. Valve landing, which usually produce chattering noises, can be improved by using a radial system. The stator current is lowered for a gentle valve landing. Furthermore, the stepping valve and its seat can both be grooved to help them grip into position during state transitions. The ultimate aim of this project is to produce an engine which can be adapted for various applications by changes in software. With this development, the essential processes to run the engine, (fuel, air, spark) will all be software controlled, leading to a more efficient, environmentally friendly, reliable and powerful engine.

The proposed rotary valve system minimises negative environmental impacts like Nitrogen Oxide (NOx) emissions since the fuel-air mixture is controlled precisely, hence sustainable manufacturing.

References

- [1] Mechadyne International Ltd, The Impact of Valve Events upon Engine Performance and Emissions. *Society of Automotive Engineers, Inc.*
- [2] S.A.G Mir Saied, S.A. Jazayeri, and A.H. Shamekhi Modeling of Variable Intake Timing in SI Engine. *Proceedings of ICES2006, ASME International Combustion Engine Division 2006 Spring Technical Conference*, May 8-10, 2006, Aachen, Germany.
- [3] J.J. Liu, Y.P. Yang and J.H. Xu, Electromechanical Valve Actuator with Hybrid MMF for Camless Engine. *Proceedings of the 17th World Congress, The International Federation of Automatic Control*, Seoul, Korea, July 6-11, 2008.
- [4] I. Zibani, R. Marumo, J. Chuma and I. Ngebani. *Software Controlled Stepping Valve System for a Modern Car Engine*. 14th Global Conference on Sustainable Manufacturing, Stellenbosch, South Africa. 3-5 October 2016.
- [5] http://www.ehow.com/how-does_4687962_timing-belt-work.html
- [6] <http://auto.howstuffworks.com/camshaft2.htm>
- [7] J.K. Taylor, *The Internal Combustion Engine in Theory and Practice*. MIT Press, 1985.
- [8] S.A.G. Saied, S.A. Jazayeri, A.H. Shamekhi, Modeling of Variable Intake Timing in SI Engine. *Proceedings of ICES2006, ASME International Combustion Engine Division 2006 Spring Technical Conference*, Aachen, Germany, 2006.
- [9] S. Fernando, *Internal Combustion Engines*. Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, 2006.
- [10] John B. Heywood. *Internal Combustion Engine Fun*. McGraw-Hill Higher Education, 1989.
- [11] Des Hammill. *How to choose Camshafts and Time Tune Them for Maximum Power*. Veloce Publishing. 2007.
- [12] J. Kim and J. Chang, A new Electromagnetic Linear Actuator for Quick Latching, *IEEE TRANSACTIONS ON MAGNETICS, VOL. 43, NO. 4, APRIL 2007*.
- [13] Lancefield, T., Lawrence, N., Ahmed, A. and Hamouda, H.B.H. 2007. "VLD" a flexible, modular, cam operated VVA system giving variable valve lift and duration and controlled secondary valve openings. Mechadyne International Ltd, Society of Automotive Engineers, Inc
- [14] Liu, J.J, Yang Y.P. and Xu, J.H. 2008. Electromechanical Valve Actuator with Hybrid MMF for Camless Engine. *Proceedings of the 17th World Congress, The International Federation of Automatic Control*, Seoul, Korea.
- [15] M. Veigel, M. Doppelbauer, Analytic Modelling of Magnetic Losses in Laminated Stator Cores with Consideration of Interlamination Eddy Currents, *IEEE Xplore*: 03 November 2016.
- [16] <http://www.superstreetonline.com/howto/engine/1306howvtectivtecworks/>.