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Original Research Article

The electromechanical control of valve timing at different supply voltages

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ABSTRACT

Electromechanical valve systems (EMS) add advantages to engines in terms of performance and emission by eliminating the limitations of conventional variable valve systems that operate mechanically. Electromechanical valve systems also eliminate the need for certain mechanical parts (such as cam shaft and valve lifters), enabling valve timing to occur at any desired rate as independent of the cam shaft of the engine. End of the experimental works on Authors' previously published papers [1], give us the idea that more investigations are required on controlling the valve timings with ideal voltages. The purpose of this study was to measure the valve profile and electrical behaviour (coil current) of an electromechanical system designed for small volume internal combustion engines at different supply voltages (24 V, 33 V, 42 V, and 48 V), low and high engine speeds (1200 rpm and 3600 rpm), different valve openings (0^o, 9^o, 18^o, 27^o, and 36^o KMA before the top dead centre), and different closing angles (27^o, 36^o, 50^o, 63^o, and 72^o KMA after the bottom dead centre). An electromechanical valve system with a supply voltage of 33 V was most suitable for low-speed engine operations in order to achieve the identified valve timing. The amount of electricity consumed by using a 33 V supply voltage instead of a 42 V supply voltage at low engine speeds in the electromechanical valve system was bottom that the amount of electricity consumed by an electromechanical valve system operated with a supply voltage of 42 V at all engine speed intervals.

Keywords: Camless engines, Electro-mechanic valve, Variable valve timings.

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1. INTRODUCTION

In general, fossil-based fuels and their derivatives, such as petrol and diesel are used to obtain motion energy in motor vehicles. The biggest disadvantage of fossil-based fuels is that it helps to generate harmful emissions, such as carbon monoxide (CO), hydrocarbon (HC), and nitrogen oxide (NOx), that threaten the health of human and the environment. Successful studies have been conducted to use alternative fuels in vehicles (such as LPG, CNG, biodiesel, and alcohol), add external systems to vehicles (such as catalytic converters), or make structural changes to systems of internal combustion engines (such as VVT) in order to reduce the harmful emissions generated by internal combustion engines.

A cam shaft is used to help open and close valve in internal combustion engines. The conventional valve system gains motion from the cam shaft, and provides constant valve timing for all engine speeds. The conventional valve system restricts the performance of internal combustion engines (low torque and high fuel consumption), especially at low and high engine speeds [1]. Variable valve systems that operate mechanically have eliminated most of these restrictions. However, variable valve systems that operate mechanically are unable to change all operating parameters (the duration the valve stays open, the valve lift, the variety of the valve's opening and closing angle, the variety of valve overlap) of valves at the same time and at infinite intervals. Electro-mechanical valve systems, which operate as independent of the cam shaft, can effectively change the operating parameters of valve both simultaneously and at infinite intervals; these systems contribute hugely to the performance of the engine and the emissions in particular.

The throttle can be eliminated and the pumping loss of the engine can be reduced by using valve systems without a cam shaft. Engine performance and emissions can be improved through filling the engine at optimum level by changing the opening and closing angle of the valve, the valve lift, and the amount of time the valve stays open. Valve systems without a cam shaft enable the inner exhaust gas recirculation, which removes the need for an external EGR. In addition, there is no need for mechanical pieces that use up the power of engine, such as the cam shaft, the valve lifters, and the valve rocker mechanism, in valve systems without a cam; as a result, the friction power improves. All the advantages listed above are part of the potential of engines without a cam shaft.

The number of studies conducted regarding electro-mechanical valve systems is increasing every day. In general, the designs are hydraulic, pneumatic, and electro-mechanical [6, 7, 8, 9, 13]. Various control techniques are being conducted to investigate the effect the designed electro-mechanical valve systems have on power consumption, the impact the valve has on the valve seat, the reaction period, and the fuel consumption needed, and optimize these parameters [10, 11, 12, 13, 18, 19]. An effective fuel economy is possible if the crank shaft angle can be transferred to the valve motion as variable [5]. Valve timing, the opening and closing duration of the valve, the transition time of the valve, and the height of the valve are all important parameters in increasing engine performance and decreasing pollutant emissions that threaten human health [2, 3, 4].

The response speed of the system does not depend on the engine load or engine speed as electro-mechanical valve systems allow operation independent of the cam shaft. The core, which is active at high engine speeds, must complete its motion as quick as possible (3 – 3.5 millisecond) [15, 16, 17]. Electro-mechanical valve systems increase engine power by 7.9%, decrease CO emission by 66%, increase HC emission by 12%, and increase NOx emission by 13% [1, 14].

In this study an electro-mechanical valve system, based on studies referred to in literature [1, 5, 10, 11, 12, 15, 17, 19, 20] regarding actuator power consumption, valve lace impact, control and welding types, was designed, manufactured and tested. EMS tests were conducted by changing the engine speed, the opening and closing angle of valves, and EMS supply voltages.

2. MATERIALS AND METHOD

The EMS system, designed based on studies referred to in literature, had an actuator that comprised of a bottom coil that enabled the valve to open, an upper coil that enabled the valve to close, a progressive-type core that moved between both coils and was attached to the stem of the valve, and two springs. Figure 1 illustrates the test mechanism and diagram of the designed and manufactured EMS actuator. Figure 2 illustrates the view from the top of the cylinder head of the EMS actuator. The EMS control unit was used to control the EMS actuator according to the engine speed and position of the piston/crank shaft. Detailed Flow diagrams of the EMS control unit was given in Appendix.

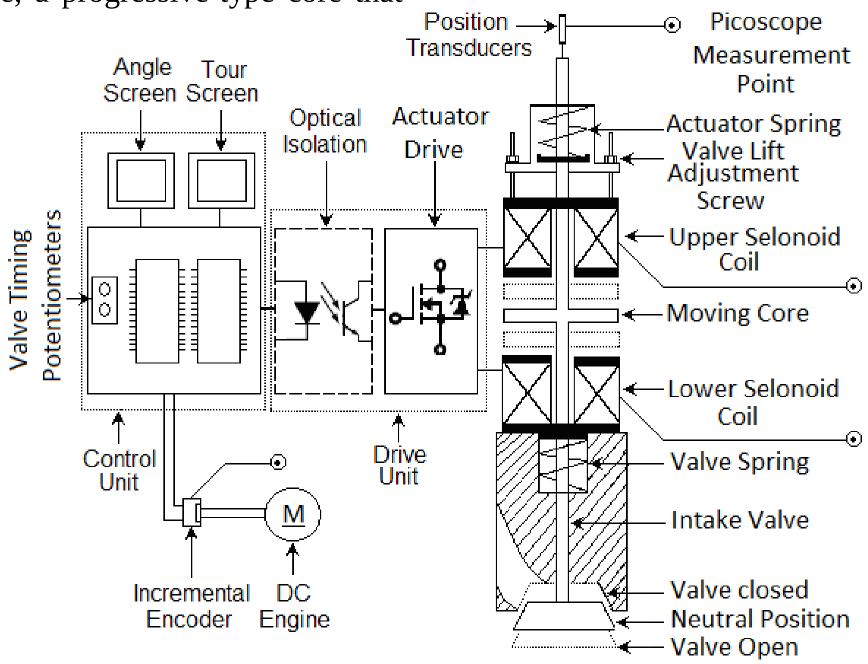

Figure 1 A block diagram of the EMS control system

The bottom coil of the EMS actuator was moved in the same direction of the valve opening. The upper coil was responsible for closing the valve. The EMS system was operable in three different positions (Figure 1). The core inside the actuator was exposed to the magnetic field of the bottom coil when EMS supply voltage was applied to the bottom coil, and moved in the direction of the opening valve. To close the valve, EMS supply voltage was applied to the upper coil, and the core between both coils was moved in the same direction of the valve closing to close the valve. Under these conditions, no voltage was applied to the bottom coil. When voltage was not applied to both coils, the core was kept at a neutral position between both coils as a result of the balance of springs at both ends.

Principally, the actuator is like an oscillating mass-spring combination and is activated by an electro-magnetic force. The potential energy is transferred between two springs via the core and the valve throughout normal operation. The voltage is applied to the relevant coil during the transition. The magnetic force formed overcomes the spring force, friction and gas flow forces in the cylinder.

The moving core completes most of its movements with the help of the energy stored in the springs. The spring force adds to the magnetic force until the point at which half of the movement length is

reached for achieving the effective coil. After that point, it imposes a force against the magnetic force. Therefore, the selection of the springs in EMS systems has great importance.
Experiment mechanism of the EMS system (Figure 1) comprised of an EMS actuator, an EMS control unit, a DC electric engine, an incremental encoder, a coil driver and insulation unit, an 18 V power supply to feed the EMS control unit, and a 50 V power supply to feed the solenoid coils. An ADC212 Picoscope was also used to measure the current of the bottom and upper solenoid coils together with the position of the valve and its encoder information (Figure 1).
The DC engine used as part of the testing stimulated the rpm of the internal combustion engine and the position information of the piston/cam shaft. The DC engine was connected to the output shaft encoder to evaluate the angular motion of the DC engine, the engine speed, the return angle, and the microprocessors of the EMS control unit. The engine speed recorded by the encoder was used to constantly monitor the opening-closing angles of the valves from the LCD screen on the EMS control system. The valve timer potentiometer on the EMS control unit can also be used to record different opening and closing angles for the valve as EMS system users.
The angle and rpm information from the encoder is processed by the EMS control unit to create an input signal for the driving unit. The upper or bottom coil is provided energy based on the information transferred from the EMS control unit to the driving unit to open or close the valve. Optic insulation was used between the EMS control unit and the driving unit so that the driver of the EMS control unit is not affected by the sudden current change.

3. RESEARCH RESULTS

The valve timing of the EMS system used in experiments was based on the standard valve timing of a single cylinder, four-cycle, upper valved KATANA 107F engine. The standard timing of the intake valve of the engine was 18˚ before the top dead centre, and 50˚ after the bottom dead centre. Figure 3 illustrates the variable valve timing used for the EMS system and adapted according to the cam profile; the angles on the cam shaft profile are stated in terms of the crank shaft. It is a known fact the ratio between the cam shaft cycle and the crank shaft cycle is ½. Therefore, the amount of angular displacement in the cam shaft is two times the amount of angular displacement in the crank shaft. Based on these figures the 36˚ angular displacement in the cam shaft, illustrated in Figure 3, is reflected as a 72˚ return angle in the crank shaft. Therefore, a full cycle of the cam shaft is the equivalent of a 720˚ angle in terms of KMA.

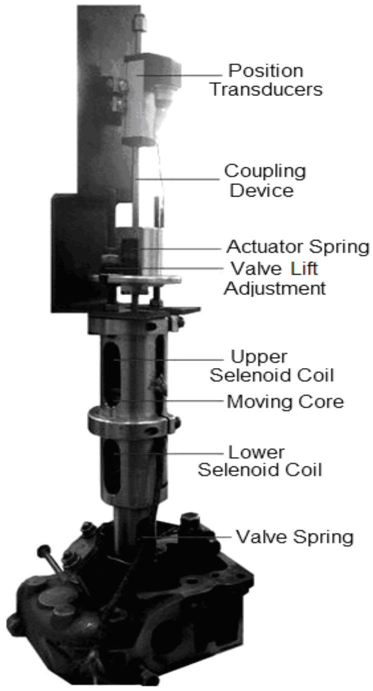

Figure 2. The view of the cylinder head of the EMS system

12 volts and multiples are used in the standard motor vehicles. Adding the 9 volt increments on top of the 24 volts give us the 33 volts and 42 volts supply voltages. Thus, the intermediate voltages may be able to examine the results on graphs.
The valve profile and electric behaviours (coil currents) of the EMS system designed for small volume internal combustion engines were measured at different supply voltages (24, 33, 42, and 48 V), low and

high engine speeds (1200 and 3600 rpm), and different opening (0°, 9°, 18°, 27°, and 36° KMA before the top dead centre) and closing angles (27°, 36°, 50°, 63°, and 72° KMA after the bottom dead centre) during this study.

First, tests were carried out according to low speed (1200 rpm) engines during experiments. The opening angle of the valve was kept constant (18° KMA before the top dead centre) at a supply voltage of 24 V, and the closing angle was changed. Experiments were repeated for EMS supply voltage of 33 V, 42 V, and 48 V. Afterwards, tests were carried out according to low speed (1200 rpm) engines by keeping the closing angle of the valve constant, and changing the opening angle of the valve for supply voltage of 24 V, 33 V, 42 V, and 48 V. The experiments conducted on a low speed engine (1200 rpm), as stated above, were repeated for a high speed engine (3600 rpm).

An ADC212 Picoscope was used to measure, and record simultaneously, the currents of the upper and bottom coils of EMS actuator, the valve profiles, the engine speed, and valve timing. Experimental studies were conducted by first deferring from the top dead centre by 9°, 18°, 27°, and 36°, and then by deferring from the bottom dead centre by 27°, 36°, 50°, 63°, and 72° (Figure 3). The EMVA (Electromechanical Valve Actuator) was operated at a speed of 1200 rpm and 3600 rpm, and for every rpm the supply voltage applied was 24 V, 33 V, 42 V, and 48 V.

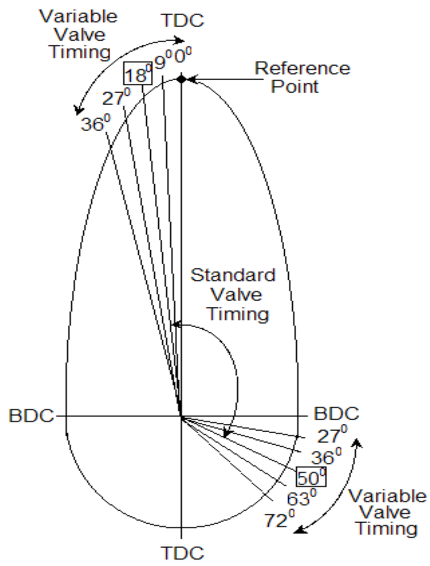

Figure 3 Standard and variable valve timing

3.1. The Image of Standard Timing of Intake Valve with an Obtained in EMVA.

Figure 4 illustrates the standard valve timing obtained in the EMVA system for an engine with a speed of 1200 rpm and a supply voltage of 24 V. Figure 4 illustrates approximately two cycles of the engine in terms of the crank shaft angle.

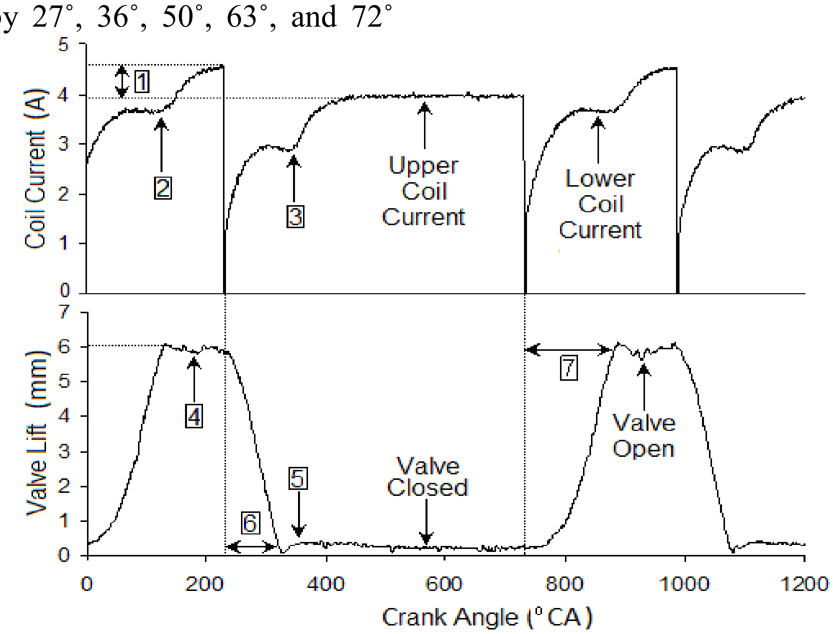

Figure 4. The image of standard timing of intake valve with a 1200 rpm and 24 V supply voltage obtained in EMVA

Point 1: Illustrates the difference between the current level of the bottom coil and the current level of the upper coil. The difference is due to the difference between the number of windings of the bottom coil (opening coil) and the upper coil (closing coil). The fact that the number of windings of the bottom coil is higher can prevent the delay that arises when the valve opens.

Point 2 and Point 3: Illustrate the bend points of the bottom and upper coil currents. At these points the valve completes its opposite direction motion, being both fully opened or fully closed. The EMVA system is comprised of two springs that are positioned opposite to one another. During operation the spring anti-motion is compressed. The power of the compressed spring helps the valve movement up to the halfway mark the minute the valve starts to move. The valve that passes the halfway mark starts to compress the spring opposite. The system requires additional power in order to keep the compressed spring balanced. Therefore, it draws a current, which starts to accelerate then stabilizes, from the source in a short period of time, once it passes the bend point.

Point 4 and Point 5: These points occur when the core, active when the valve is fully opened or fully closed, collides with the coil surface. The core, active when the valve is fully opened or fully closed, rebounds when it hits the coil surface. The rebound for the designed system was between 0 mm and 0.25 mm. Figure 4 illustrates the valve height graph; overall oscillations continue. A Linear Voltage Differential Transformer (LVDT) that operates according to the resistive principle was used to measure the valve profile. It is possible to reflect all vibrations at the output for all states due to its infinite resolution property and the fact that it is installed directly to the stem of the valve (Figure 2). The fact that EMVA system is used on a real engine installing the LVDT directly to the stem of the valve is key to foresee the amount of vibration the valve will be exposed to.

Point 6 and Point 7: Illustrates the time difference between when the bottom or upper coil is powered and when the valve completes its turn in the direction of the powered coil. Electro-mechanical systems require a certain amount of time to convert electric energy to mechanical energy. This is something that directly affects the response speed of electro-mechanical systems. Therefore, delays may arise when completing the motion. The supply voltage and the operating speed of EMVA system are important parameters in completing the valve movement.

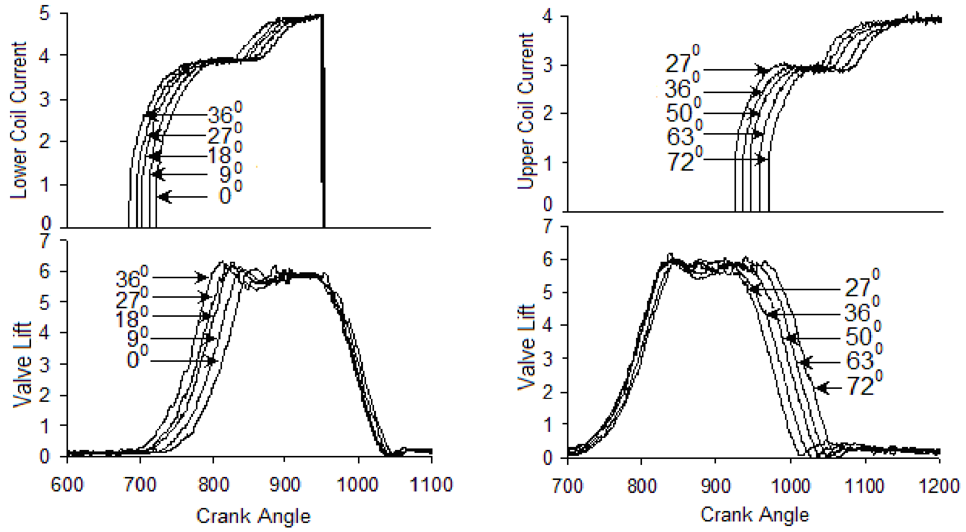

Figure 5. 1200 rpm 24 volt opening and closing

3.2. 24 Volt Opening and Closing

The prepared EMS control system (Figure 1) was connected to the prototype EMVA (Figure 2). The desired advance measurements were adjusted by hand by reading the valve timing adjustment potentiometers using the developed software. The potentiometers were recorded real time, and the desired valve timing was carried out. Data gather using a Picoscope during experiments was loaded onto the computer as Excel data. The data was illustrated as graphs without filtering.

Figure 5 and Figure 6 illustrate results for EMVA system operated at different speeds with a supply voltage of 24 V. While Figure 5 illustrates the bend points of coil currents (Point 2 and Point 3 in Figure 4), there are no bend points illustrated in Figure 6 for the bottom coil current. When the operating speed was tripled, the intake time decreased to a third of its initial value (inversely proportional). Figure 6 illustrates that the time (idle time) between when the bottom and upper coils are triggered and when the valve completes its motion was maximum (Point 6 and Point 7 in Figure 4). The completion of the valve motion was delayed due to insufficient supply voltage.

The change in the voltage applied to the coils causes a change in the magnetising flux [21]. The magnetic flux will decrease at low supply voltage. The decrease in flux will cause a decrease in the magnetic attraction force that affects the core. As illustrated in Figure 6, there was a delay in the completion of valve motion.

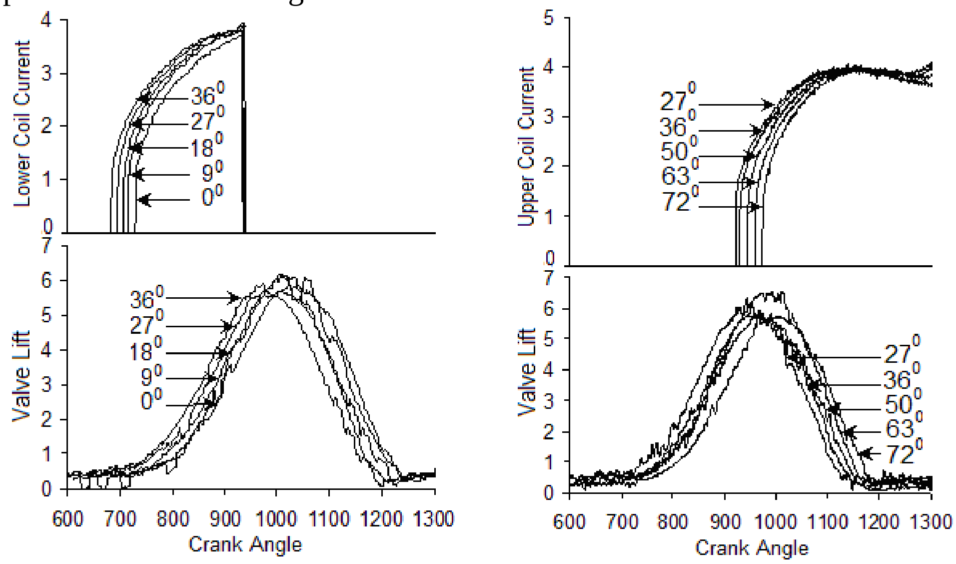

Figure 6. 3600 rpm 24 volt opening and closing

3.3. 33 Volt Opening and Closing

Figure 7 and Figure 8 illustrate results for experiments conducted at a supply voltage of 33 V. Increasing the supply voltage enabled better-distinguished valve height graphs in Figure 7 and Figure 8. The increase in the supply voltage applied to the magnetic circuit increases the magnetic flux density that has an effect on the core [16, 21].

The increase in flux density increases the collision intensity between the the core and the coil surface; referred to as 4 and 5 in Figure 4, and more distinguished in Figure 7 and Figure 8. Point 6 and Point 7 in Figure 4 illustrate that the time (idle time) between when the bottom and upper coils are triggered and when the valve completes its motion decreased based on the increase in magnetic flux. The valve motion was completed over a shorter period of time at a supply voltage of 33 V. The fact that the valve motion is completed over a shorter period of time allows the damping of the contra electromagnetic force formed on the coil.

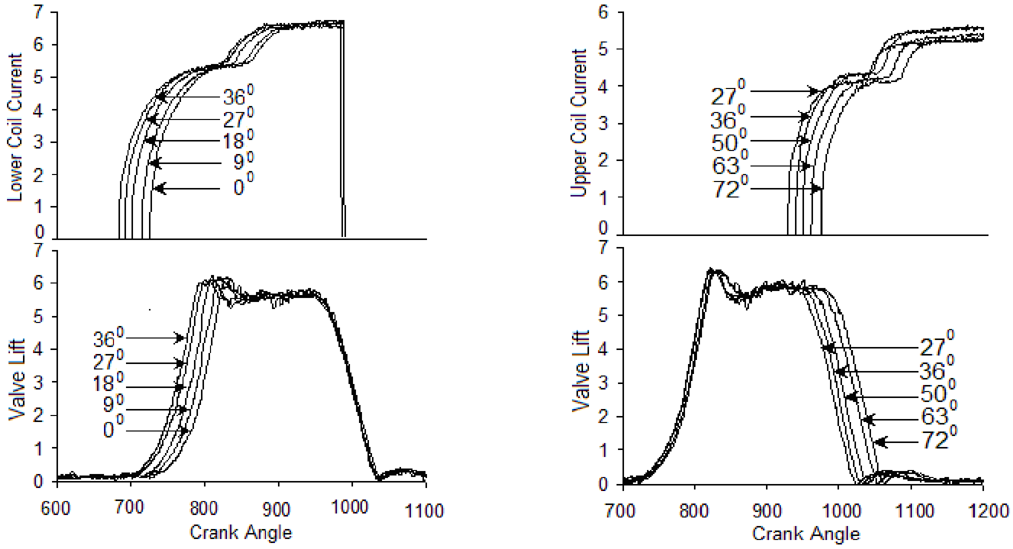

Figure 7 1200 rpm 33 volt opening and closing

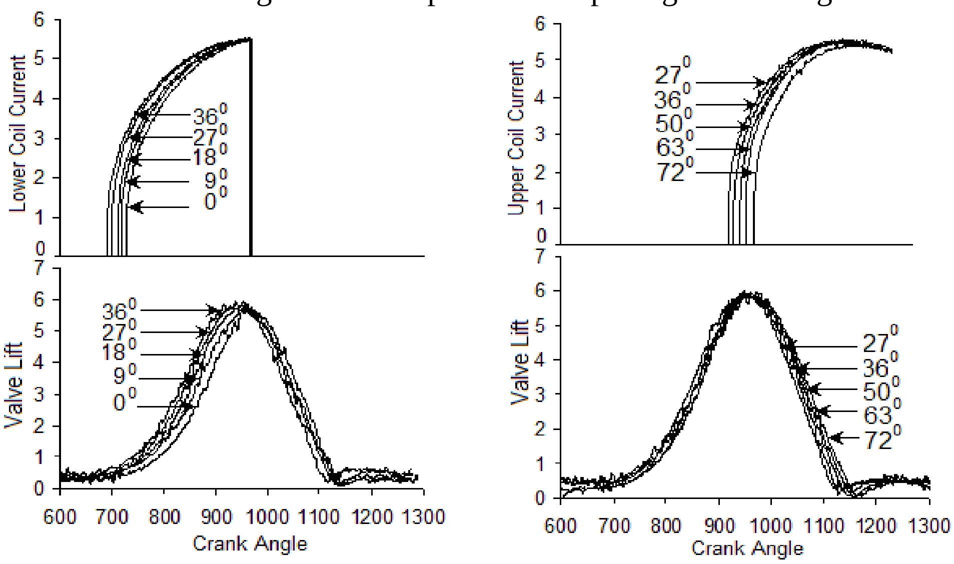

Figure 8 3600 rpm 33 volt opening and closing

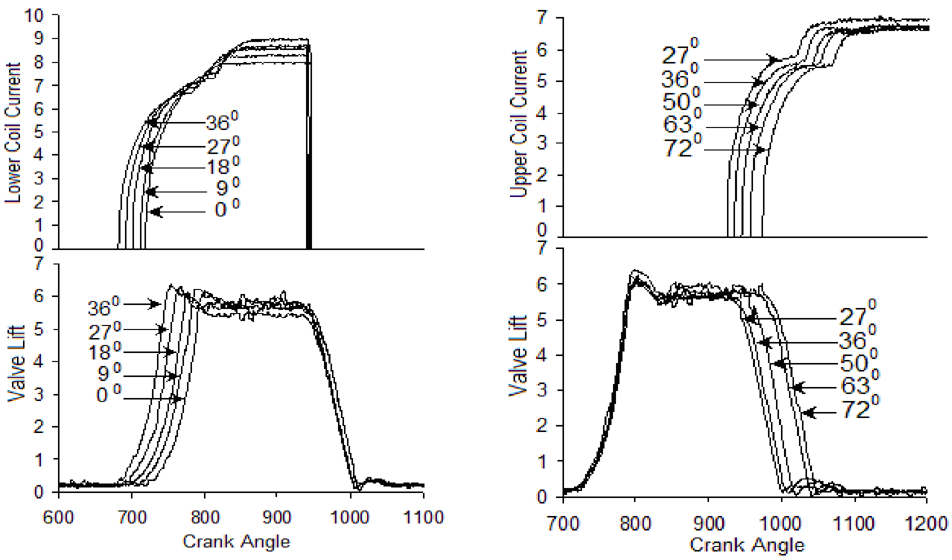

Figure 9 1200 rpm 42 volt opening and closing

3.4. 42 Volt Opening and Closing

Figure 9 and Figure 10 illustrate results for a supply voltage of 42 V; the bottom coil current increased to 8A, and the upper coil current increased to 7A together with the increase in the supply voltage. While the geometry of the disc-type progressive core between both coils, and its distance to both coils, and the coils did not change, the fact that the core was affected more by the magnetising field produced by the coils was based on the current level [20].

The fact that the magnetic field is more forceful increases the intensity at which the valve sits on the valve seat. The completion of valve motion was shorter at both engine speeds together with the increase in the supply voltage.

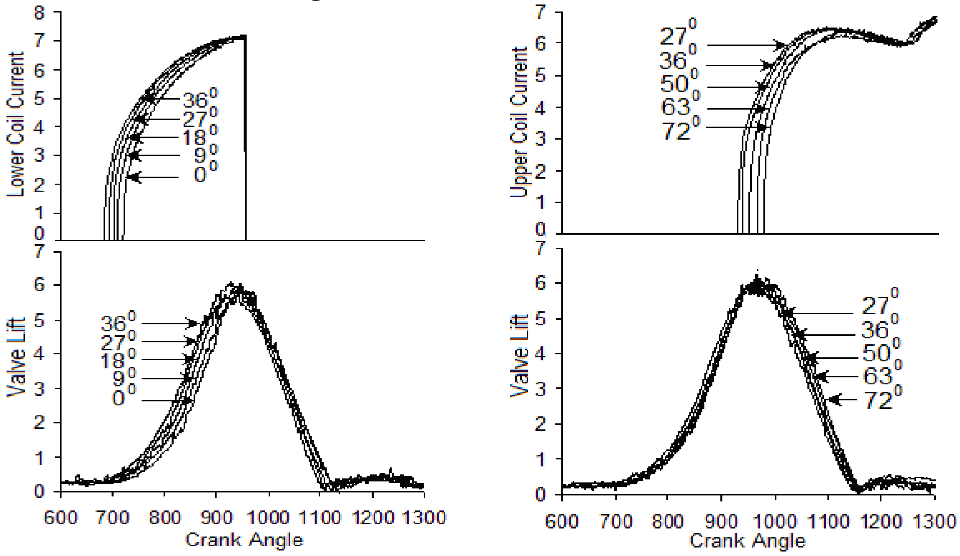

Figure 10 3600 rpm 42 volt opening and closing

3.5. 48 Volt Opening and Closing

Increasing the supply voltage of the EMVA system to 48 V maximised the attraction force the core was exposed to. The rebound of the core after colliding with the coil surface (Point 4 and Point 5 in Figure 4) was at its most significant (maximum) in Figure 11 and Figure 12.

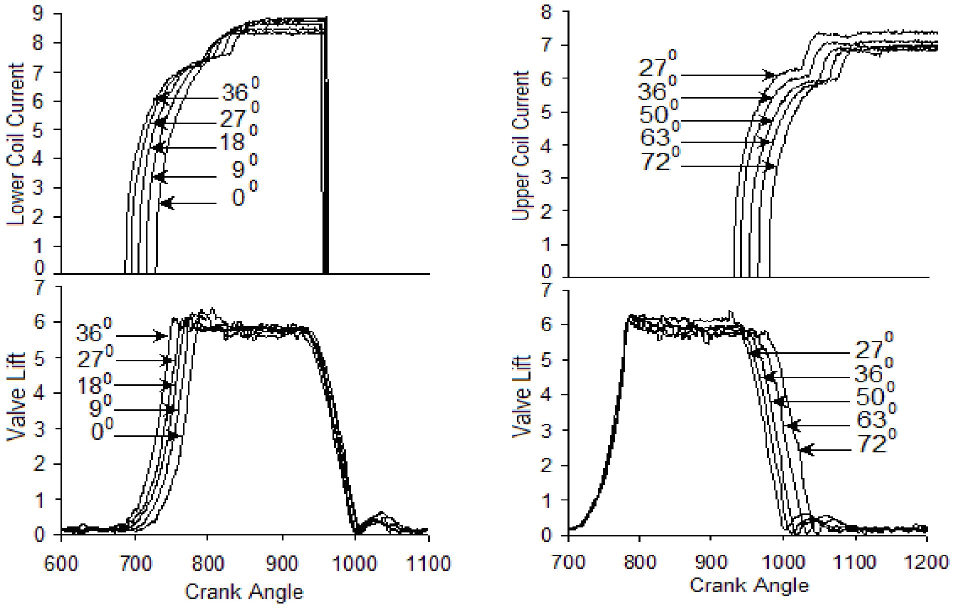

Figure 11 1200 rpm 48 volt opening and closing

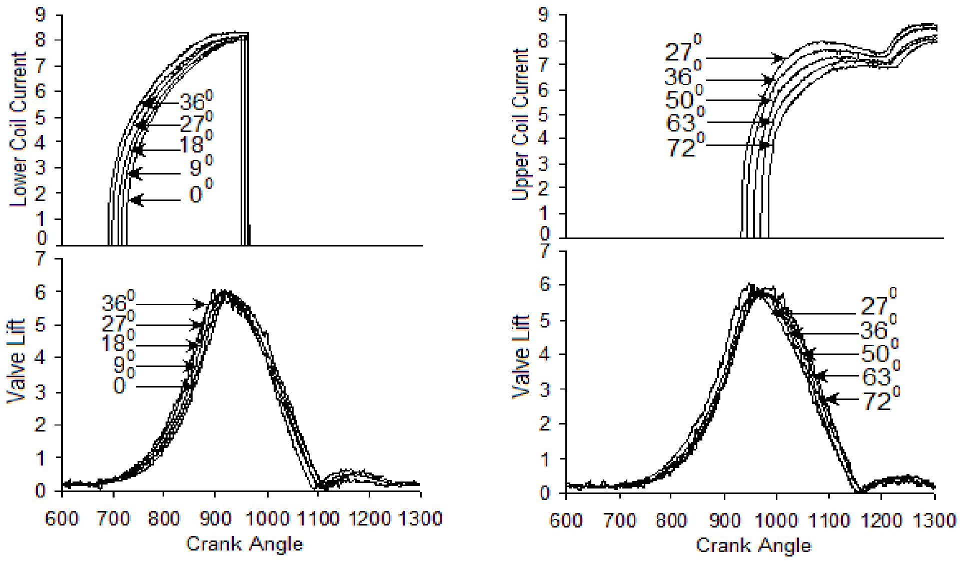

Figure 12 3600 rpm 48 volt opening and closing

4. EXPERIMENTAL RESULTS AND DISCUSSION

Similar results were obtained in terms of the time it took the valve to complete its motion at an engine speed of 1200 rpm and an engine speed of 3600 rpm, and supply voltages of 42 V and 48 V. Variable valve timing was conducted in an EMVA system, inspired by the standard valve timing of the engine, in this study. The study graphically sets forth variable valve timing at different operating speeds, and different supply voltages.

The increase between 24 V and 33 V was sufficient to achieve valve movement for an engine with a speed of 1200 rpm. A supply voltage of 24 V was inadequate to achieve valve movement for an engine with a speed of 3600 rpm.

In this study, variable valve timing was achieved using an electro-mechanical valve system at both low and high speeds, and the effects different supply voltages had on the valve timing were investigated.

■ The electro-mechanical valve mechanism was designed so that it was user-controlled.

■ Variable valve timing was conducted at four different values nine degrees above and below the standard valve timing of an internal combustion, single cylinder engine.

■ The change in the valve angle of the designed system was achieved at for a wide range, which was 72˚ in terms of crank shaft angle.

■ An element that operates in accordance with the resistive principle (infinite resolution) was used to measure valve movement; the effects on the valve movement were illustrated with graphs.

■ The EMVA control system was operated at low and high speeds at four different supply voltages thanks to the designed control and driving units, and graphical results were discussed.

■ Study results concluded that a supply voltage of 33 V was suitable for low-speed engine operations in achieving the indentified valve timing.

■ This study will help to understand the effect a change in speed and supply voltage has on variable valve timing.

In the future, using the EMVA system on a real engine will help to investigate further the effects on contra electromagnetic force has on system and energy consumption.

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APPENDIX

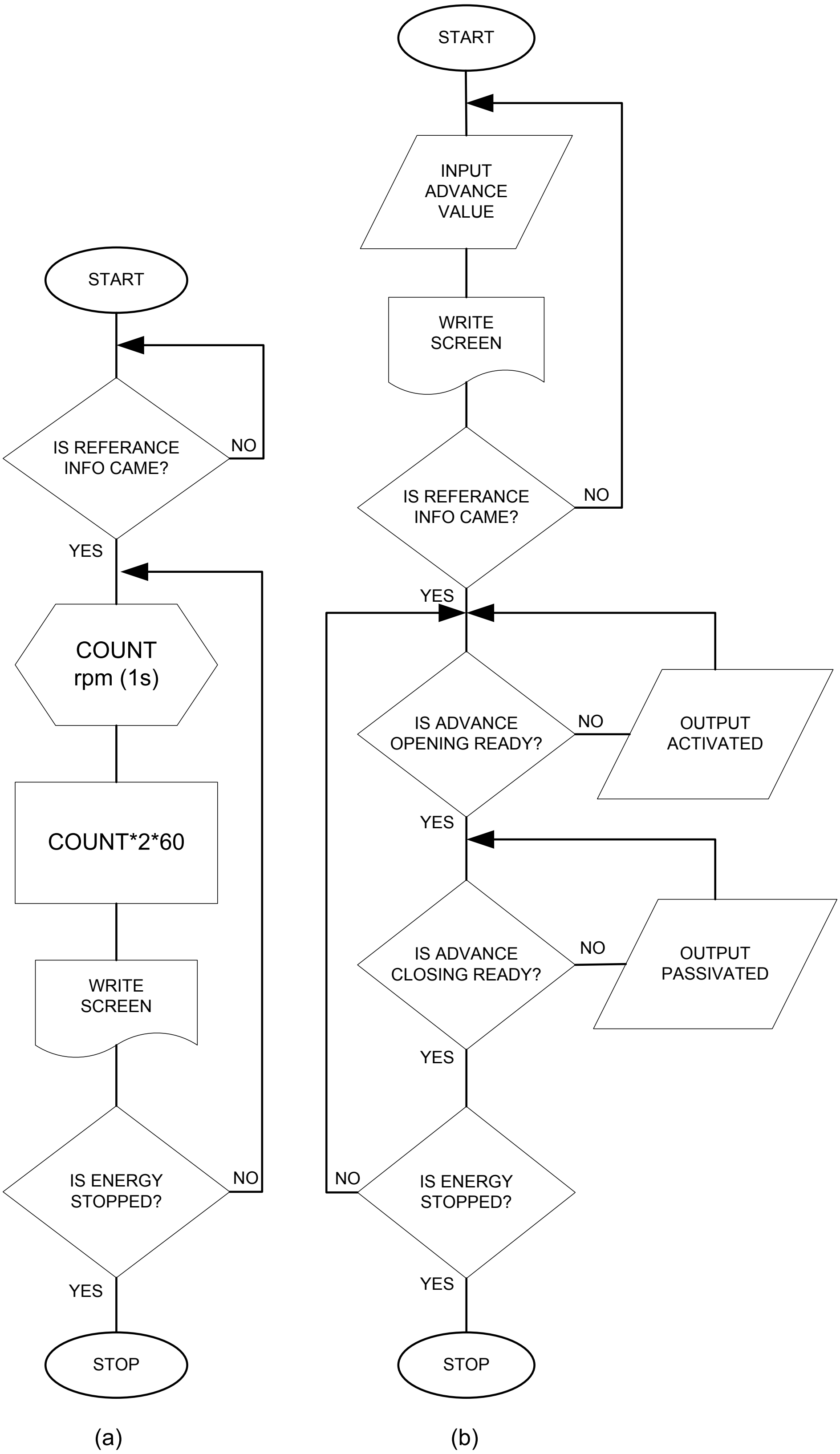

Figure A1. Flow diagrams of the Control Unit;
a) Engine speed
b) Position of the Piston/Crankshaft angle