

DEVELOPMENT OF EXTENDED RANGE AND BLENDED  
CONTROL MODULE FOR PLUG-IN HYBRID AIR  
MOTORCYCLE

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**BORANG PENGESAHAN STATUS TESIS♦**

JUDUL: **DEVELOPMENT OF EXTENDED RANGE AND BLENDED  
CONTROL MODULE FOR PLUG-IN HYBRID AIR  
MOTORCYCLE**

SESI PENGAJIAN: 2012/2013

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DEVELOPMENT OF EXTENDED RANGE AND BLENDED CONTROL MODULE  
FOR PLUG-IN HYBRID AIR MOTORCYCLE

MOHAMAD SHAHIR BIN MOHAMED NAFI

A report submitted in partial fulfillment of the requirements  
for the award of the degree of  
Bachelor of Mechanical Engineering with Automotive

Faculty of Mechanical Engineering  
UNIVERSITI MALAYSIA PAHANG

JUNE 2013

**EXAMINER'S APPROVAL DOCUMENT****UNIVERSITI MALAYSIA PAHANG  
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## ABSTRACT

Research and development in internal combustion engine shows variety of possibility. As the engine technology getting smarter and complex, simple concept of using power source from nature such as air is almost forgotten. In this project, an internal combustion engine using gasoline has gone through some modification with the aim of using compressed air as the source of power for some part of trips. This kind of technology called as air hybrid engine. Air hybrid engine is capable of utilizing the high pressure compressed air as power source to move pistons in engine cylinder. To control this system, a blended control module was developed by using an open-source Programmable Interface Controller (PIC) which is smaller and powerful microcontroller. Other components such as sensor also had been used in this project. The overall control that had been developed is a closed-loop control system where a closed-loop control system is one in which control action is dependent on the output and have feedback function. Main purpose of this project is to make an idea become alive. This project will mainly concerned on controlling the different mode of engine by using microcontroller PIC16F876A coupled with speed sensors. A program in MikroC is written and developed to communicate with the microcontroller according to plan sequences. A schematic design and simulation in Proteus Professional is created first to see whether it functioning or not before a prototype board can be developed. For purpose of voltage regulation, a single-pole double throw (SPDT) relays are used as “OUTPUT” signal from the sensor for the microcontroller. The “OUTPUT RELAY” is of the 5V SPDT powered from the switching output voltage 5V DC of the microcontroller. The application that is going to be developed must be in a low cost and a small scale basis. Subsequently, experimental simulation tests will be conducted to evaluate the response and accuracy behavior of the microcontroller before the control module can be developed. As for the result, a control module circuit prototype has been developed and it is ready to be tested with the engine.

## ABSTRAK

Kajian dan perkembangan dalam bidang enjin pembakaran dalam menunjukkan pelbagai kemungkinan. Disebabkan teknologi enjin yang semakin pintar dan kompleks, konsep yang mudah dengan menggunakan sumber kuasa dari alam semula jadi seperti udara hampir dilupakan. Dalam projek ini, enjin pembakaran dalam yang menggunakan petrol telah melalui beberapa pengubahsuaian dengan tujuan untuk menggunakan udara termampat sebagai sumber kuasa untuk sebahagian perjalanan. Teknologi ini dipanggil sebagai enjin hibrid udara. Enjin hibrid udara mampu menggunakan udara termampat bertekanan tinggi sebagai sumber kuasa untuk menggerakkan ombok dalam silinder enjin. Untuk mengawal sistem ini, satu modul kawalan telah dibangunkan dengan menggunakan Programmable Interface Controller (PIC) yang lebih kecil dan ia merupakan mikropengawal yang berkuasa. Komponen lain seperti sensor juga telah digunakan dalam projek ini. Kawalan keseluruhan yang telah dibangunkan adalah sistem kawalan gelung tertutup di mana sistem ini adalah salah satu tindakan kawalan yang bergantung kepada output dan mempunyai fungsi maklum balas. Tujuan utama projek ini adalah untuk menjadikan sesebuah idea itu hidup. Projek ini terutamanya akan mengambil berat mengenai kawalan mod enjin yang berbeza dengan menggunakan mikropengawal PIC16F876A yang ditambah dengan sensor kelajuan. Satu program ditulis dan dibangunkan dengan menggunakan MikroC untuk berkomunikasi dengan mikropengawal untuk bergerak mengikut urutan pelan. Satu skema reka bentuk dan simulasi menggunakan Proteus Professional dicipta untuk melihat sama ada ia berfungsi atau tidak sebelum prototaip litar boleh dibangunkan. Bagi tujuan aturan voltan, relay (SPDT) digunakan sebagai isyarat "OUTPUT" daripada sensor untuk mikropengawal. "OUTPUT RELAY" adalah dari relay (SPDT) 5V yang berkuasa dari pensuisan voltan 5V DC. Aplikasi yang akan dibangunkan mestilah dalam kos yang rendah dan secara kecil-kecilan. Selepas itu, ujian simulasi eksperimen akan dijalankan untuk menilai tingkah laku dan ketepatan mikropengawal sebelum ia boleh dibangunkan. Hasilnya, satu litar prototaip modul kawalan telah dibangunkan dan ia sedia untuk diuji bersama enjin.

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**LIST OF SYMBOLS**

$K_p$	Controller Gains
$K_i$	Controller Gains
$K_d$	Controller Gains
$u(t)$	Control Signal
$e(t)$	Difference Between Desired and Actual Value (Control Error)
$V_d$	Displacement Volume
$\eta$	Efficiency
$\Delta H$	Enthalpy Difference
$W_i$	Indicated Work
$I_L$	Load Current
$D_p$	Protection Diode
$h_{FE}$	Transistor Current Gain
$V_s$	Voltage Supply

**LIST OF ABBREVIATIONS**

AM	Air Motor
ANSI	American National Standards Institute
ATDC	After Top Dead Center
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ECU	Electronic Control Unit
CB	Compression Braking
IMEP	Indicated Mean Effective Pressure
PHV	Pneumatic Hybrid Vehicle
CAD	Crank angle degrees
TDC	Top Dead Center
BDC	Bottom Dead Center
IVO	Intake Valve Open
IVC	Intake Valve Close
EVO	Exhaust Valve Open
EVC	Exhaust Valve Close
PID	Proportional Integral Derivative
COP	Coefficient of Performance
RPM	Revolution Per Minute
PCB	Printed Circuit Board
PIC	Programmable Interface Controllers
PWM	Pulse With Modulation
ISIS	Intelligent Schematic Input System

ARES	Advanced Routing and Editing Software
LCD	Liquid Crystal Display
CNC	Computer Numerical Control
THT	Through Hole Technology
SMT	Surface Mount Technology
ROM	Read Only Memory
RAM	Random Access Memory
EEPROM	Electrically Erasable Programmable Read-Only Memory
IDE	Integrated Development Environment
SPST	Single Pole Single Throw
SPDT	Single Pole Double Throw



## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 BACKGROUND STUDY**

In order to reduce emissions, fuel consumption is a main factor in the development of the automotive field nowadays and the hybridization of engines is a way to make this happened. The development of plug-in hybrid air engine will greatly reduce the petroleum use because this technology provides the potential to replace a significant portion of transportation petroleum consumption by using compressed air for part of the trips. A plug-in hybrid air engine allows the option of having the operation and range of conventional motorcycle on longer trips with the help of internal combustion engine.

The purpose of plug-in hybrid air engine is to make the motorcycle is no longer dependent on a single fuel source. One of the advantages of plug-in hybrid air engine is their capability to integrate the transportation and compressed air power generation systems in order to improve the efficiency, fuel economy, and reliability of both systems with some modification of the internal combustion engine. To ensure the optimum running for the motorcycle, an engine control module for the hybrid air engine was developed in order to communicate and control the actuators in the engine.

#### **1.2 PROBLEM STATEMENT**

In order to sustain the future of nature due to the increasing on exhaust emission, a hybrid system was developed since long years ago. However, hybrid system also has its significant problems where they require two propulsion systems, which take up

space, add weight and greatly increase the cost. Thus, the development of hybrid system did not survive the continuity because the engine that simply powered by another propulsion such as air motor generator requires a big air tank for compression process, and at the same time it is also lacking in mileage and not so powerful compared to conventional internal combustion engine.

Another challenge is that the suitable control of the operation of the engine is necessary to achieve much of the efficiency benefits and to avoid drivability problems such as difficulty with transmission shifting to something as simple as starting the car, which was not possible with mechanical control only. The performance and emissions that today's engines deliver would be impossible without the electronic controls that manage everything from ignition and fuel delivery to every aspect of emissions control. Electronic controls make possible engines that deliver excellent good fuel economy and will limit the pollution. So, the development of a suitable control module for the hybrid air engine is essential because it has the ability to control some modified parts in engine to refill the tank with compressed air only when the amount of compressed air in the tank becomes too low and the process will continue to get the optimum range of journey.

### **1.3 OBJECTIVES**

The objectives of this study are as follows:

- a. To develop a blended control module for plug-in hybrid air engine using Proteus Professional and MikroC software.
- b. To test the engine control module at the hybrid air engine.

### **1.4 SCOPE**

The scope of this study are as follows:

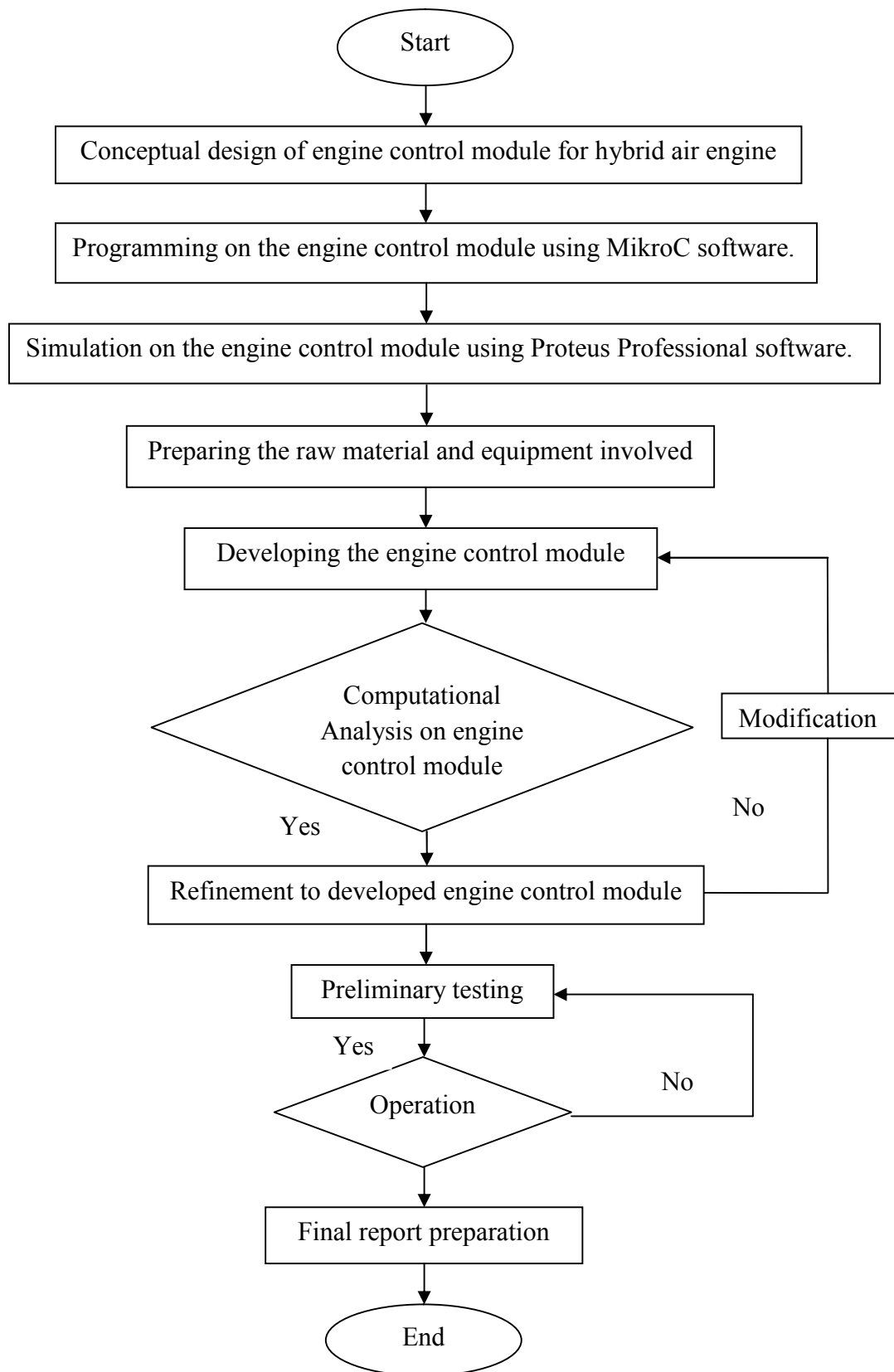
- a. Conceptual design on the engine control unit for plug-in hybrid air engine.
- b. Development of programming using MikroC software.

- c. Simulation on the engine control unit using Proteus Professional software.
- d. Preparing the raw materials and equipment involved.
- e. Developing the engine control unit prototype.
- f. Documentation.

## **1.5 HYPOTHESIS**

At the end of the project, it was expected the prototype of engine control unit for plug-in hybrid air engine with blended mode provided is completed and ready for testing with the Subaru EA71 boxer engine, where this engine will serve as a potential and economic modification platform for hybrid engine development, which consists of internal combustion, air compression and innovated air powered cylinders integration.

## 1.6 FLOW CHART



## **1.7 GANTT CHART**

Refer to APPENDIX A.

## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2.1 AIR HYBRID VEHICLES**

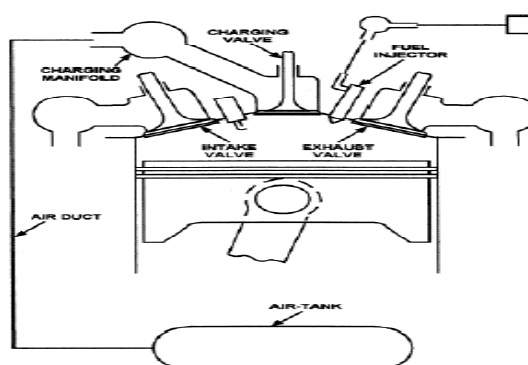
Hybrid electric vehicles (HEVs) have overcome production limits and are regarded as one of the most effective and feasible solutions to current environmental concerns. Hybrid electric vehicles (HEVs) use two sources of energy which are fossil fuel and electrochemical energy stored in batteries. They are usually comprised of an internal combustion engine (ICE) and an electric motor. Hybrid electric vehicles (HEVs) are able to store the vehicle's kinetic energy in the shape of electrochemical energy in a battery by running the electric motor as a generator. Despite the beneficiary improvements that this kind of vehicle provides, there are some serious concerns about hybrid electric vehicles (HEVs) performance (Amiri, 2009).

The hybrid electric vehicles (HEVs) Powertrain system is complex, which introduces a very complicated control problem and increases the maintenance cost of the vehicle. Using a battery in the Powertrain is also a problem for hybrid electric vehicles (HEVs) because battery-charging efficiency is highly dependent to the charging strategy (Amiri, 2009), and the state of charge of the battery which forms the basis of the vehicle control strategy cannot be precisely defined (I. Kim, 2006). In addition, hybrid electric vehicles (HEVs) are 10% to 30% heavier than ICE based vehicles (Guzzella, 2007).

Compared with a hybrid electric vehicle, an air hybrid based vehicle could provide a better efficiency with less complexity, weight and cost. In 1999, Schechter proposed the idea of an air hybrid engine for the first time. The idea evolved from the

fact that the internal combustion engine can be run as a compressor and an air motor by changing the valve timing. Schechter has introduced a new cylinder head configuration in which there is an extra valve connecting the cylinder to an air tank, called the charging valve. This extra valve is active only when the engine works as a compressor or air motor. The valve sends the pressurized air from the cylinder to the air tank, and vice versa. He also studied the thermodynamic cycle of each mode. He reported more than a 50% reduction in fuel consumption by using the air hybrid engine in a 45 second driving cycle (Schechter, 1999).

In 2000, Schechter published his second paper. He used the same cylinder head configuration, but showed that by changing the valve timings, different engine loads can be achieved. He suggested that approximately 30 liter air-tank volume per 1000 kg of the vehicle mass is needed for a gasoline engine, and suggested a new definition of regenerative efficiency. Efficiency is defined as a fraction of the energy absorbed during braking that can be used in the subsequent acceleration. Based on a rough calculation, Schechter reported an efficiency of 74% for the regenerative braking system during the braking of a typical vehicle from an initial speed of 48 km/hr (Schechter, 2000). In 2007, Schechter patented the two-stage air hybrid configuration in which, some of the engine cylinders receive atmospheric air and after compression, transfer it to an intermediate air tank. Other cylinders receive compressed air from the intermediate tank and compress it further (Schechter, 2007).



**Figure 2.1:** Schechter's proposed configuration

Source: Schechter (1999)

After these initial investigations on the air hybrid engine concept, there are research groups at different universities and research centers started investigating this new concept.

### **2.1.1 UCLA Research Group**

In 2003, Tai, C in collaboration with Ford Motor Company proposed a new cylinder head configuration which enabled different modes of operation without adding an extra valve to the head. The group utilized four fully flexible camless valves for each cylinder, two intakes, and two exhausts. In this configuration, one of the intake valves is switchable, and connects either the intake manifold or air tank to the cylinder with a three-way valve. The group also optimized the valve timings according to the desired load, the tank pressure, and speed. The researchers claimed a 64% and 12% fuel economy improvement in city and highway driving, respectively. This improvement is reported to be partly due to using the camless valvetrain which permitted the engine to run unthrottled. They have provided no experimental results, but did use GT-POWER to simulate the proposed air hybrid engine configuration (Tai, C, 2003).

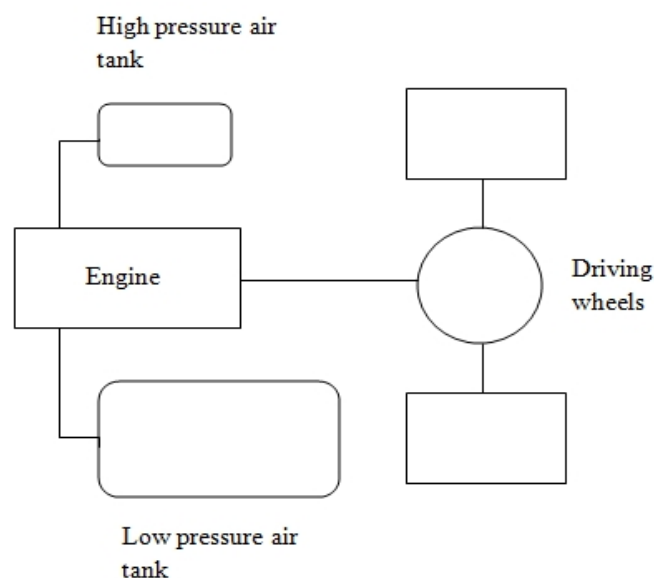
In 2008, they published their first experimental work on an air hybrid engine in collaboration with Volvo and Sturman Industries. They converted a six-cylinder diesel engine to an air hybrid engine utilizing a Sturman hydraulic camless valvetrain. They optimized the valve timings of the air motor (AM) and compression braking (CB) modes at two engine speed and three tank pressures, and implemented the obtained valve timings experimentally. They also reported the transient performance of the engine in switching from the compression braking (CB) to the air motor (AM) modes (Kang, 2008).

### **2.1.2 Lund Institute of Technology**

In 2005, Andersson, M from the Lund Institute of Technology proposed a regenerative braking system with two tanks for a typical city bus. They concluded that the regenerative braking system with only one tank was not capable of producing high enough torque in the compression braking (CB) or air motor (AM) modes. Thus, the



idea was to use a pressure tank as a substitute for the atmosphere as the supplier of the low-pressure air. The proposed configuration is shown in Figure 2.2. In this configuration, the engine works between a 600 liter low-pressure and a 145 liter high-pressure tank at different modes of operation. The engine cylinders are charged with the air from the low-pressure tank, which has a higher pressure compared to the ambient during braking. In the proposed configuration, the low-pressure tank must be replenished by an on-board compressor on a regular basis. They reported an average efficiency of 55% for the regenerative braking system and a 22% fuel consumption saving in a typical urban driving cycle obtained through simulations (Andersson, 2005).



**Figure 2.2:** Air hybrid concept using two tanks

Source: Andersson (2005)

Later, in 2007, Trajkovic, S., from the same research group published the experimental results of an air hybrid engine. They converted a single-cylinder diesel engine to an air hybrid engine. Pneumatic valve actuators were used to make the air hybrid configuration possible. Two modes which are compression braking (CB) and air motor (AM), were tested and studied in this work. The Engine's Indicated Mean Effective Pressure (IMEP) and tank pressure were reported for different valve timings

and engine speeds at the air motor (AM) and compression braking (CB) modes. A new definition of efficiency was also presented, based on the negative and positive Indicated Mean Effective Pressure (IMEP) at the compression braking (CB) and consequent air motor (AM) modes. An efficiency of 33% for the regenerative braking system was reported (Trajkovic, S, 2007).

They published their second investigation on the same air hybrid engine in 2008. They optimized the valve timings for the compression braking (CB) and air motor (AM) modes at various tank pressures. Additionally, they modified the tank valve diameter to increase the system efficiency. They showed that, by using a larger charging valve, the efficiency of the regenerative system, based on their definition of efficiency, could be increased to approximately 44%. They also compared the experimental results with GT-POWER results and found them to be in agreement.

In their next study, they validated an engine model in GT-Power by the experimental results and used the GT-Power model to study the effect of different parameters such as tank valve diameter and valve timings on pneumatic hybrid performance. In 2010, they published the driving cycle simulation results of their single-cylinder air hybrid engine. They chose a lower limit of 8 bars for the tank pressure and reported a reduction in the fuel consumption up to 30% in the Braunschweig driving cycle (Trajkovic, S, 2010).

### **2.1.3 National Taipei University of Technology**

In addition to the information about air hybrid structures, there is also a totally different configuration of an air hybrid, proposed by Huang, K. D., Tzeng, S. C. in 2004. In this configuration, a typical internal combustion engine (ICE) was connected to a screw compressor and operates at the engine's most efficient point. Then, a pneumatic motor is driven by the compressed air to generate power. Thus, the main difference between the proposed air hybrid configuration and a series hybrid electric vehicle is that an air compressor replaces the generator, a pneumatic motor replaces the electric motor, and a high-pressure air tank replaces the battery. They achieved an 18% improvement in efficiency, compared with that of an internal combustion engine (ICE) based

powertrain. However, they have not considered the effect of the vehicle weight increase due to adding extra components such as pneumatic motor and compressor on the overall efficiency of the vehicle (Huang, K. D., Tzeng, S. C., 2004).

## 2.2 CONTROL SYSTEM OF THE PNEUMATIC (AIR) HYBRID

The pneumatic hybrid vehicle (PHV) concept is a low-cost if compared with electric hybrid. The pneumatic hybrid vehicle (PHV) concept comprises no additional propulsion source and a pressure tank as an energy storage device. The main idea with the pneumatic hybrid is to use the internal combustion engine (ICE) in order to compress atmospheric air and store it in a pressure tank when decelerating the vehicle. The stored compressed air can then be used either to accelerate the vehicle or to supercharge the engine in order to achieve higher loads when needed (Sasa Trajkovic, 2010).

The pneumatic hybrid engine configuration comprises a dedicated tank valve or charging valve that controls the flow of compressed air into or out from a pressure tank connected to the tank valve port on the cylinder head. All valves are controlled by a fully variable valve actuating system. The operation of the different pneumatic hybrid engine modes of operation must be explained first before some important performance parameters can be explained. By plotting the cylinder pressure against corresponding cylinder volume, a PV-diagram is generated (Sasa Trajkovic, 2010). The area enclosed by the PV-diagram is the indicated work ( $W_i$ ) done by the gas on the piston:

$$W_i = \int p dv \quad (2.1)$$

The load of the engine can be expressed as the indicated mean effective pressure (IMEP). It is a quantity related to the indicated work output of the engine independent of engine displacement which makes comparisons between different engines of different sizes possible. It is defined as the ratio of indicated work to the engine displacement:

$$\text{IMEP} = W_i / V_d \quad (2.2)$$

In the following sub-section the most important pneumatic hybrid engine modes of operation will be thoroughly discussed.

### **2.2.1 Compressor Mode**

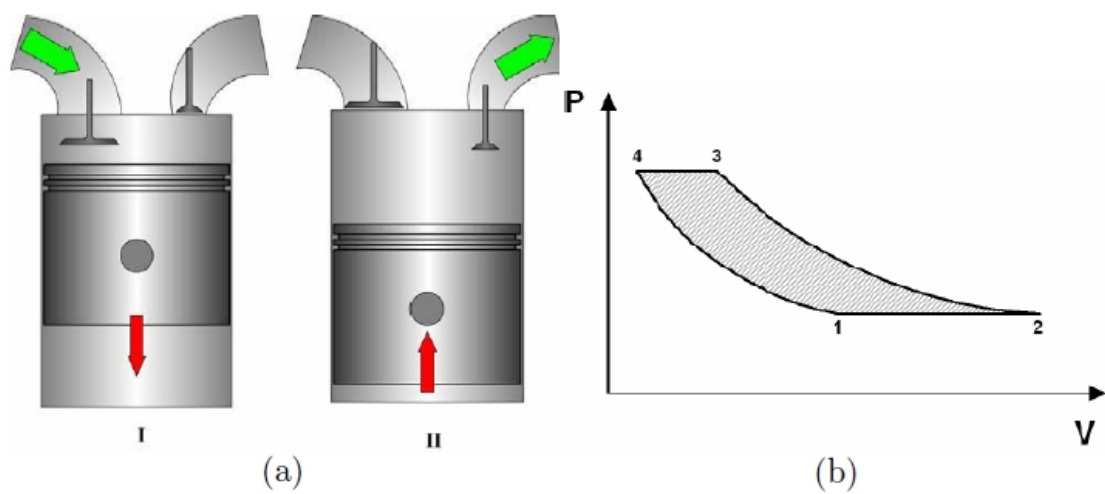
In compressor mode, the engine is utilized as a 2-stroke compressor in order to decelerate the vehicle. The kinetic energy of the moving vehicle is converted to potential energy in the form of compressed air (Sasa Trajkovic, 2010). The ideal operating principle of the compressor mode can be explained with references to Figure 2.3. The numbers in brackets refer to the numbers in the PV-diagram displayed in Figure 2.3 (b).

1 - 2: Intake stroke. During compressor mode operation the inlet valve opens a number of crank angle degrees (CAD) after top dead center (ATDC) and fresh air is brought into the cylinder (1). At the end of the intake stroke, as the piston reaches bottom dead center (BDC), the inlet valve closes (2).

2 - 3: Compression stroke. The moving piston starts to compress the air trapped in the cylinder as it ascends away from bottom dead center (BDC). The compression stroke ends at the moment the tank valve opens.

3 - 4: Charging period. The charging period is the period during which the compressed air is transferred from the cylinder into the pressure tank. It starts when the tank valve opening (TankVO) occurs. The opening is set to occur somewhere between bottom dead center (BDC) and top dead center (TDC) (3), depending on how much braking torque is needed. For instance, a very early tank valve opening (TankVO) means that there will be a blow down of pressurized air into the cylinder, and the piston has to work against a much higher pressure, thus a higher braking torque is achieved. The charging period proceeds as long as the tank valve is open. The tank valve closing (TankVC) occurs shortly after top dead center (TDC) (4). At this point the cylinder contains compressed air at the same pressure level as the air in the tank.

4 - 1: Expansion stroke. As the piston descends away from top dead center (TDC), the compressed air trapped in the cylinder expands and the intake valve opening (IVO) occurs when ambient pressure is reached in the cylinder (1). A too early intake valve opening (IVO) means that there will be a blow down of the compressed air trapped in the cylinder into the intake manifold, thus useful energy is wasted. A too late intake valve opening (IVO), on the other hand, leads to over-expansion of the air trapped in the cylinder which results in the generation of vacuum. Since this is an energy consuming process, the net result will be an increase in negative load.

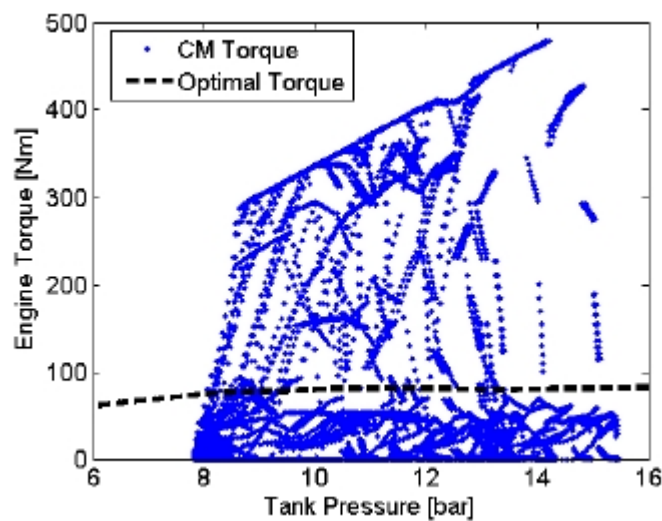


**Figure 2.3:** (a) Illustration of compressor mode operation, I) Intake of fresh air, II) Compression of air and pressure tank charging; (b) Cylinder pressure during ideal compressor mode operation presented as a function of cylinder volume in a PV-diagram

Source: Sasa Trajkovic (2010)

By operating the compressor mode according to the description given above maximum compressor mode efficiency will be achieved. However, during real driving, the braking power generated during compressor mode operation, will vary according to the current driving conditions. This means that an ideal operation cannot be maintained at all time and thus the compressor mode efficiency will decrease (Sasa Trajkovic, 2010).

The important aspect of the pneumatic hybrid concept is its ability to control the amount of braking torque generated at a specific time during compressor mode operation. As stated earlier, the load demand during compressor mode operation will be far from optimal in terms of efficiency. In Figure 2.4, the compressor mode torque distribution as a function of tank pressure during a standard driving cycle, in this case the Braunschweig cycle, is illustrated.



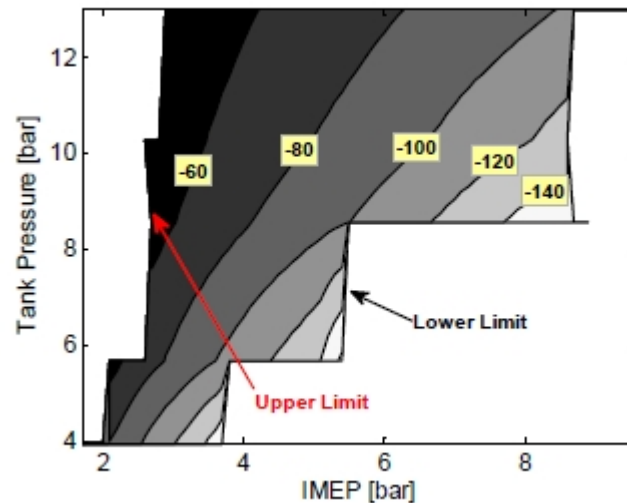
**Figure 2.4:** Torque distribution during compressor mode operation as a function of tank pressure during the Braunschweig driving cycle

Source: Sasa Trajkovic (2010)

The torque data is supplemented by data from optimal compressor mode operation visualized as a dashed line in present figure. It can clearly be seen that most of the operating points will deviate considerably from optimal operation. This leads to the conclusion that running the engine only in optimal operating points is not realistic. The load will depend on the driving conditions and the tank pressure. Therefore, the need for a more advanced load control is evident.

The development of the load controller was done in two steps. At first, a feedforward controller was tested. The feedforward controller contains valve timing data acquired from steady-state experiments at different loads and tank pressures (Sasa

Trajkovic, 2010). The results are displayed in Figure 2.5 in the form of a tank valve opening (TankVO) map.

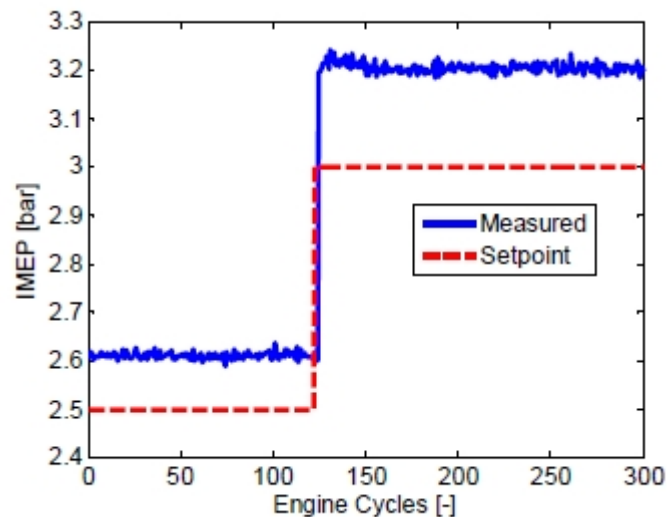


**Figure 2.5:** Illustration of the feedforward load controller map of the TankVO as a function of both IMEP and tank pressure. TankVO is expressed in CAD ATDC

Source: Sasa Trajkovic (2010)

From the Figure 2.5, it can be noticed that the compressor mode operation is limited on two fronts. The occurrence of the lower limit can be explained by inadequate amount of tank pressure which prevents the compressor mode operation to achieve higher loads. For instance, at a tank pressure of 5 bar the maximum achievable load is almost 4 bars. The maximum load is achieved when the tank valve opens at bottom dead center (BDC). At this point, maximum charging capacity of the cylinder has been reached and the cylinder cannot be filled with any additional amount of pressurized air, and hence a further increase in load in this tank pressure cannot be achieved. The occurrence of the upper limit shown in Figure 2.5 can be explained by improper valve actuator function. A low load demand at a high tank pressure will lead to a tank valve opening (TankVO) close to top dead center (TDC) and since tank valve closing (TankVC) occurs at top dead center (TDC) or shortly after a too short tank valve duration can be expected. With extremely short tank valve durations, the stability of the valve actuators deteriorates considerably (Sasa Trajkovic, 2010).

In order to ensure proper valve actuator functionality at all times both limits have been implemented as constraints in the control program. The feedforward controller takes the measured load and tank pressure from the previous engine cycle as inputs and with the help of the map presented in Figure 2.5, the controller outputs proper steady-state valve timings at current tank pressure and load.



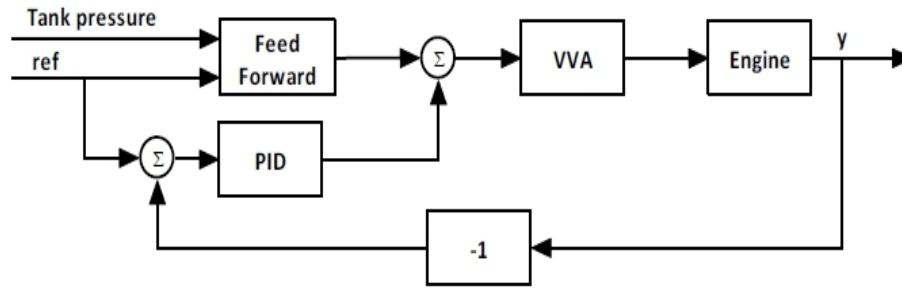
**Figure 2.6:** Process response to a set-point change in IMEP when using feedforward load controller during compressor mode operation at a steady-state tank pressure of 5 bars

Source: Sasa Trajkovic (2010)

In Figure 2.6, the process response to a set point change in indicated mean effective pressure (IMEP) when using the previously described controller can be seen. The process variable deviates from the set point both before and after the load step, which indicates the disadvantage with using a pure feedforward controller. The reason for this behavior is that the conditions in- and outside the engine might not be the same as at the time the valve timing maps used with the feedforward controller were generated. Factors like intake air temperature, engine oil and coolant temperatures and valve actuator nonlinearities contribute considerably to this type of behavior.



In order to avoid the unwanted behavior described above, a closed-loop controller has to be added to the control system. The feedforward was combined with an ordinary Proportional Integral Derivative (PID) controller. The task of the controller is to eliminate any steady-state error while minimizing rise time and settling time of the process response when subjected to a set-point change.



**Figure 2.7:** The closed-loop control system for compressor mode load control. Proper valve timings are calculated as the sum of the feedforward term and the output from the PID controller

Source: T. Glad and L. Ljung (2008)

The proportional–integral–derivative (PID) controller can be described by the following equation (T. Glad and L. Ljung, 2008):

$$u(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(\tau) d\tau + K_d \cdot \frac{d}{dt} e(t) \quad (2.3)$$

### 2.2.2 Air Motor Mode

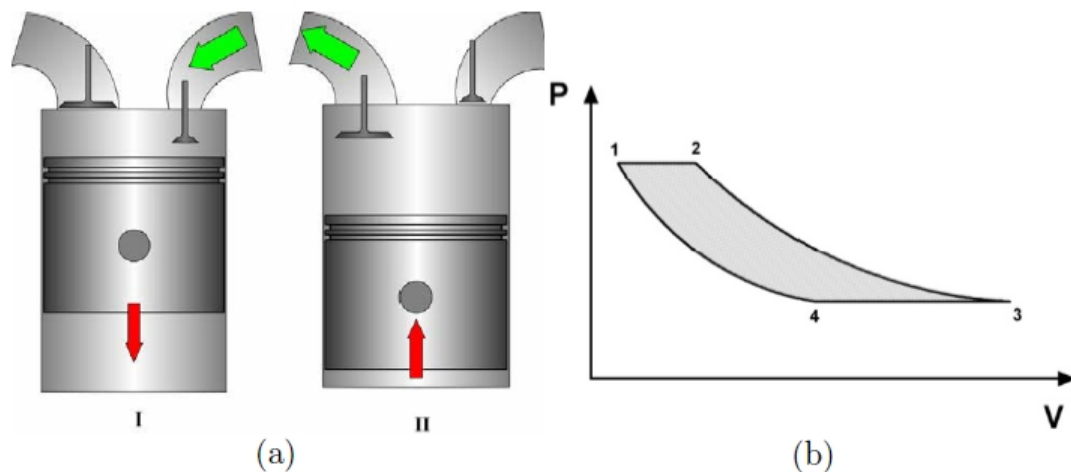
In air-motor mode, the engine is utilized as a 2-stroke air-motor that uses the pressurized air from the pressure tank in order to accelerate the vehicle. The potential energy stored in the tank in the form of pressurized air is converted to mechanical energy on the crankshaft which in the end is converted to kinetic energy. The ideal operating cycle of air-motor mode can be explained with references to Figure 2.8. The numbers in brackets refer to the numbers in the PV-diagram displayed in Figure 2.8 (b).

From the observation, the ideal PV-diagram for the air - motor mode is the same as for the compressed mode, just reversed (Sasa Trajkovic, 2010).

1 - 2: Charging period. During an air motor (AM) the tank valve opening (TankVO) occurs at top dead center (TDC) or shortly after (1), and the pressurized air fills the cylinder to give the torque needed in order to accelerate the vehicle. Somewhere between top dead center (TDC) and bottom dead center (BDC) the tank valve closes (2), depending on how much torque the driver demands. Increasing the tank valve lift duration will increase the amount of pressurized air charged to the cylinder which in turn results in an increased torque generated by the pressurized air.

2 - 3: Expansion stroke. As the piston descends away from top dead center (TDC), the pressurized air contained in the cylinder is expanded. The expansion stroke ends at bottom dead center (BDC) (3) at which point the inlet valve opens.

3 - 4: Exhaust stroke. As the piston ascends away from bottom dead center (BDC) the air contained in the cylinder is expelled to the inlet manifold. Closing of the inlet valve occurs somewhere between bottom dead center (BDC) and top dead center (TDC) (4), and the timing is selected in such a way that when the piston reaches top dead center (TDC), the air trapped in the cylinder is compressed to the same level as the tank pressure.



**Figure 2.8:** (a) Illustration of air-motor mode operation, I) Charging of the cylinder with pressurized air, II) Air venting; (b) Cylinder pressure during ideal air motor mode operation presented as a function of cylinder volume in a PV-diagram

Source: Sasa Trajkovic (2010)

However, during real driving the demanded load during air motor mode will be determined by the current driving conditions which consequently mean that the air-motor mode operation will deviate from the ideal case substantially. A high load demand means that the charging period will be extended. This might lead to a situation where the pressure at the end of the expansion stroke is above atmospheric pressure resulting in a blow down of pressurized air into the intake manifold at the time of inlet valve opening (IVO). This is a waste of useful energy and such operation of air motor (AM) should be avoided as much as possible

### 2.2.3 Pneumatic (Air) Hybrid Efficiency

The efficiency of compressor and air-motor modes are important parameters and can be used to determine proper valve timings, valve diameter etc. The intuitive definition of the compressor mode efficiency would be the ratio of the energy transferred to the pressure tank and the energy consumed by the engine. However, the air that is drawn into the cylinder during the intake stroke already contains energy. The enthalpy of air at an ambient temperature of 20°C is about 293 kJ/kg (Y.A. Cengel and

M.A Boles, 2002). This means that the energy transferred to the tank during compressor mode consists of both the energy of the air drawn into the cylinder during the intake stroke and the energy transferred from the engine to the air during the compression stroke. Hence, the compressor mode efficiency as defined above can attain values higher than unity. Therefore, the efficiency of compressor mode is more appropriately defined in terms of the coefficient of performance COP:

$$\text{COP} = \Delta H_{\text{tank}} / W_{\text{engine}} \quad (2.4)$$

Where  $\Delta H_{\text{tank}}$  is the enthalpy transferred to the tank per cycle and  $W_{\text{engine}}$  is the engine work output per cycle. The COP as defined above corresponds to the definition used for heat pumps (Y.A. Cengel and M.A Boles, 2002). The enthalpy of a system is defined as:

$$H = U + pV \quad (2.5)$$

Where  $U$  is the internal energy of the system,  $p$  and  $V$  are the pressure and volume, respectively, of the system. The internal energy of a system can be expressed as:

$$U = mC_v T \quad (2.6)$$

By inserting (2.6) in (2.5) followed by differentiation the change in enthalpy can be expressed as:

$$dH = mC_v dT + C_v T dm + V dp + p dV = 0 \quad (2.7)$$

If equation (2.7) is applied to the pressure tank, the last term should be deleted since the volume of the tank is constant. The air-motor mode efficiency can be defined as the ratio between the work produced by the engine and the energy transferred from the pressure tank to the cylinder:

$$\eta_{\text{AM}} = W_{\text{engine}} / \Delta H_{\text{tank}} \quad (2.8)$$

Another important parameter is the regenerative efficiency which serves as an indicator of how much of the energy absorbed during braking that can be regenerated into useful work. It is defined as the ratio between the work generated by the engine during air motor mode operation and the work absorbed by the engine during compressor mode operation:

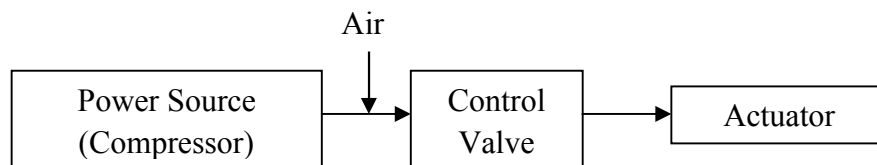
$$\eta_{\text{regen}} = W_{\text{AM}} / W_{\text{CM}} \quad (2.9)$$

### 2.3 ELECTRO-PNEUMATIC SYSTEM

Generally, pneumatics deal with systems that operated with highly compressed air or inert gases to impart power. It can also be defined as the study of movement of air. Fundamentally, pneumatic system is applying force to a gaseous fluid like air and transmits pneumatic pressure all through the fluid and converting the stored energy back into mechanical force, before work could be done. The automated systems that use electro-pneumatic technology are formed by mainly three kinds of elements, which are:

- a. Power source
- b. Control valve
- c. Actuator

The basic elements of a pneumatic system are shown in Figure 2.9.



**Figure 2.9:** Basic elements of a pneumatic system

Compressor reacts as a power source that increases the pressure of the air to provide power to move the actuator. The control valves will control the direction of flow and pressure of the actuator hence regulates the flow of pressurized air from

compressors to the actuators. This valve can be actuated manually, pneumatically or electrically depending on the design.

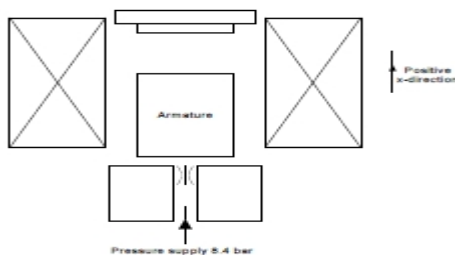
### **2.3.1 Power Source**

Power is required to convert energy from one form to other convenient form and then transfer it to the point where power is required. The power medium must be suitable for the machine where work is to be done. For pneumatic cases, compressor is the heart of any pneumatic system where it converts mechanical energy to pneumatic energy by generating compressed air. However, the compressed air generated is contaminated. Process to contaminants in the compressed air is called as preparation or conditioning.

### **2.3.2 Control Valve**

A solenoid valve is an electromechanical valve where its dynamic behavior has an influence on the fluids such as liquid or gas and can be divided into two main parts which are a solenoid and a movable armature. The solenoid valve consists of a coil of wire wound in the form of a cylinder. The coil covers the moving armature that is mounted on a spring that keeps the valve in its initial position. The valve can be activated by applying current to the coil, and the armature will move away from its initial position. As it is shown in Figure 2.10, the interior of a solenoid valve has a complex technical system.

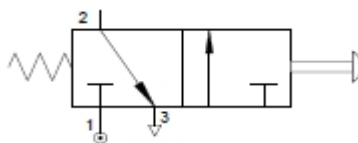
It contains four subsystems that all are related to each other which are electrical, magneto-dynamic, mechanical and fluid dynamical. When current is applied to the system, a magnetic field is induced around the coil contributing to a magnetic force. The magnetic force tries to overcome the counteracting forces, for example spring force and friction forces, resulting in opening or closing of the valve, depending on if the valve is normally open or closed. Valves are divided into different groups, according to their function and use.



**Figure 2.10:** The interior of a solenoid valve

Source: Maisam Jeddi Tehrani (2008)

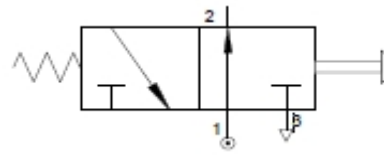
As stated before, a valve can be normally open or normally closed. Figure 2.11 shows a valve that is normally closed and not affected by external forces, and then the flow path 1-2 will be closed while the flow path 2-3 will be open.



**Figure 2.11:** Normally closed 3/2 valve - Unaffected, where number 1 is the pressure source, number 2 denotes the outlet port and number 3 is the air exhaust port

Source: Maisam Jeddi Tehrani (2008)

If the valve is affected by external forces such as in Figure 2.12, the drain will close and the path 1-2 will open. Only in this case a flow from the inlet port to the outlet port can take place. For a normally open valve, in the unaffected case, path 1-2 is open and 2-3 is closed. When the valve was affected with this construct, the drain will open and path 1-2 will close.



**Figure 2.12:** Normally closed 3/2 valve - Affected, where number 1 is the pressure source, number 2 denotes the outlet port and number 3 is the air exhaust port

Source: Maisam Jeddi Tehrani (2008)

### 2.3.3 Actuator

Pneumatic actuator is one of the important parts in this project. It is an output device that converts energy contained in the compressed air into motion. Basically, pneumatic actuators can be categorized into two types which are linear actuators that convert pneumatic energy into straight line mechanical energy and rotary actuators that convert pneumatic energy into rotary mechanical energy (Joji, P., 2010). In this project, the power cylinder in the engine will be functioning as an actuator.

## 2.4 SENSOR

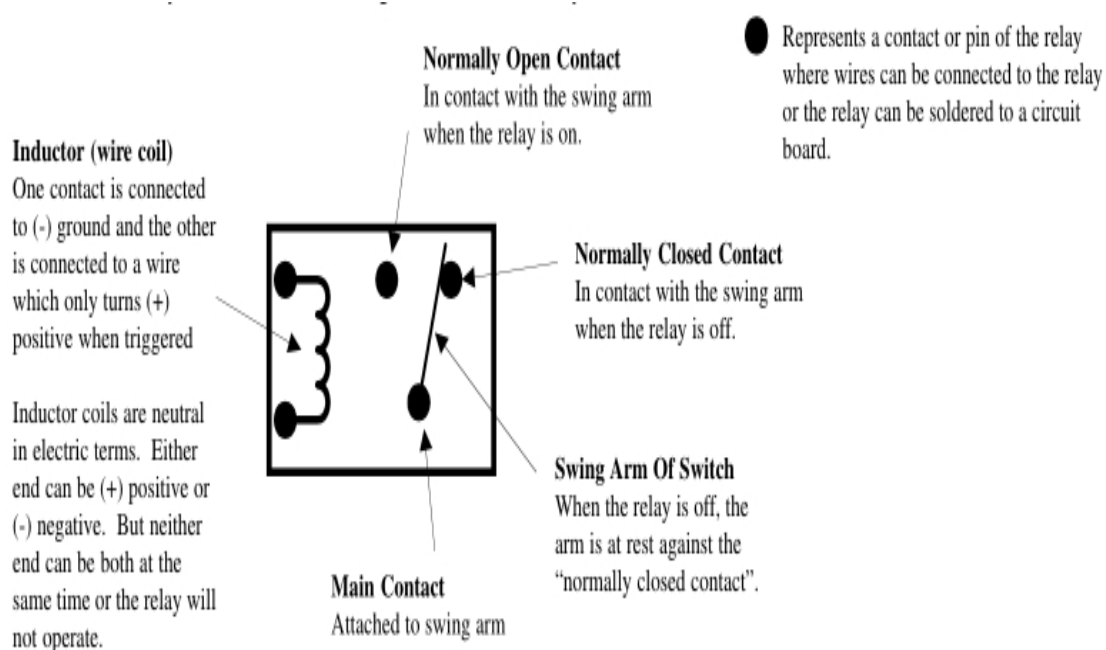
A sensor is a device for converting a physical variable, such as distance, pressure, temperature and so on. A sensor can detect whether a particular operation or event in the system has been completed or not, and then it can generate an output signal to indicate this detection. This signal can be fed back to the associated system controller for triggering the start of the action. In this project, a proximity sensor has been used to recognize the speed of the vehicle. An electronic proximity sensor actually is an inductive sensor which its function is to detect metallic objects without touching them through an electromagnetic field. Therefore, it is very suitable to detect the speed of an object.



## 2.5 RELAY

A relay is an electromechanical switch. Relays are used to switch voltages and electronic signals. No human interaction is required for the switching to occur. The electronic pulses will perform the switching. Basically, a relay operates based on the principles of electromagnetism. Inside a relay, there is a wire coil that will generate a magnetic field when there is an electric pulse flow around it.

The relay is on when an electric pulse is sent to the relay, the swing or switching arm of the switch moves to another contact of the switch. The arm moves as the generated magnetic field pulls the swinging arm toward the inductor or wire coil. More illustrated regarding to its basic principles is elaborated below.



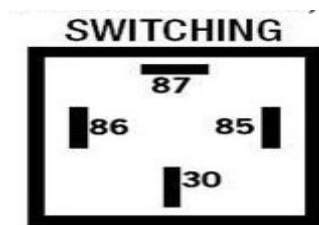
**Figure 2.13:** Basic relay

Source: The Install Doctor (1998)

There are various types of relays out there in the market. However, there are only three types of relays that are commonly used. They are Single Pole Single Throw (SPST) Relay and Single Pole Double Throw (SPDT) Relay.

### 2.5.1 Single Pole Single Throw (SPST)

A very popular automotive relay is a little black cube about an inch on a side. If it has 4 prongs, it is called a Single Pole Single Throw. Number 30 and 87 are in normally open condition while its actuating coil is located between prong number 85 and 86.

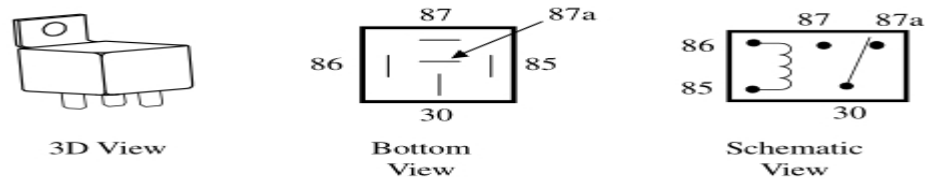


**Figure 2.14:** SPST symbol

Source: Jones, C. (2008)

### 2.5.2 Single Pole Double Throw (SPDT)

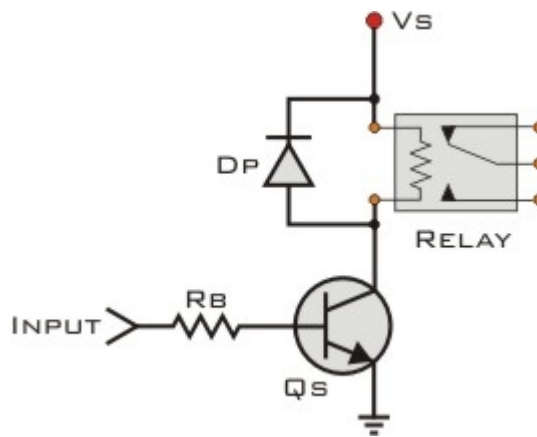
SPST will become a SPDT relay when an 87a prong is added. The magnetic coil is still located between prong 85 and 86. Common or negative commonly is supplied at terminal 30. This relay can be used to either open a circuit or close a circuit, or it can be used to switch one circuit on through terminal 87 while switching another circuit off through prong 87a. These relays can handle 12 volts at some prescribes maximum amperage, usually 30 or 40 amps. A higher rating is better for longer life.



**Figure 2.15:** SPDT symbol

Source: The Install Doctor (1998)

## 2.6 TRANSISTOR CIRCUIT



**Figure 2.16:** Basic transistor circuit

Source: G. Lazaridis (2009)

Figure 2.13 shows the basic transistor relay driver, actuated on high input. The circuit will switch on relays at lower power output such as a microcontroller. It is used to switch high loads or loads that need higher voltage to operate. The relay will be actuated during input of the circuit goes high. The protection diode,  $D_P$  is used to protect the transistor from the reverse current generated from the coil of the relay during the switch off time. Values for  $R_B$  and  $Q_S$  vary accordingly. The way to calculate the component is:

First the load current is calculated:

$$I_L = V_s / R_L \quad (2.10)$$

Then transistor current gain,  $h_{FE}$  is calculated. Its value must be at least 5 times the load current  $I_L$  divided by the maximum output current from the input to the base of the transistor.

$$h_{FE} (\text{min}) > 5 \times I_L / I_{\text{INPUT}} \quad (2.11)$$

Next, base resistor  $R_B$  shall be calculated. If the input is taken from a component such as a microcontroller that uses the same power supply as the transistor ( $V_s$ ), then the form is:

$$R_B = 0.2 \times R_L \times h_{FE} \quad (2.12)$$

Otherwise, if the component uses another power source like  $V_{CC}$  then the form is:

$$R_B = (V_{CC} \times h_{FE}) / (5 \times I_L) \quad (2.13)$$

All of equations above are provided by G. Lazaridis (2009).

## 2.7 MICROCONTROLLER

The PIC is a family of Harvard architecture microcontrollers made by Microchip Technology, derived from the PIC1640 originally developed by General Instrument's Microelectronics Division. The name PIC initially referred to "Programmable Interface Controller", but shortly thereafter was renamed "Programmable Intelligent Computer". PICs are popular with developers and hobbyists alike due to their low cost, wide availability, large user base, extensive collection of application notes, availability of low cost or free development tools, serial programming and reprogramming with flash memory capability.

A microcontroller is the combination of a microprocessor, memory, input and output ports and some of the special functions like timer, analogue to digital converter, mathematics processor and PWM generator in one chip. A microcontroller is a computer with most of the necessary support chips on-board. It has several things in common with computer, namely:

- a) A central processing unit (CPU) that executes programs.
- b) Random-access memory (RAM) where it can store data that is variable.
- c) Read only memory (ROM) where programs to be executed can be stored.
- d) Input and output (I/O) devices that enable communication to be established with the outside world.

There are countless of microcontroller in the market which range from 8 bit, 16 bit to the more advanced 32 bit. The higher the value of a bit, more performance will be provided by the microcontroller. Designers can use a microcontroller to gather input from various sensors then command a set of functions or even use the output of microcontroller for something worthy. A microcontroller is often small and low cost however it may be chosen to minimize size and to be as inexpensive as possible. To build a basic microcontroller circuit, it must consist of 3 basic circuits (Jazari2u, 2010). These three circuits are crucial to build a microcontroller system.

a.

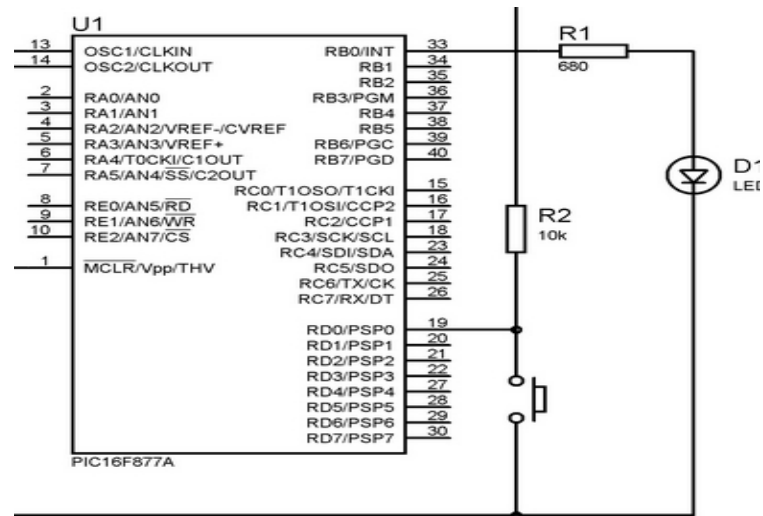


Figure 2.17: Push button circuit

Source: www.electrosome.com (2013)

The push button is used to reset the microcontroller to zero memory.

b.

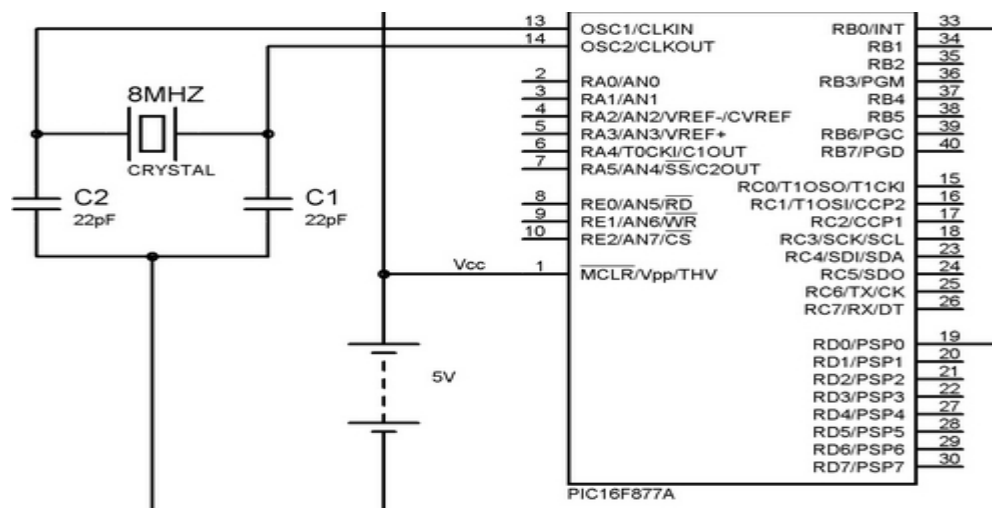
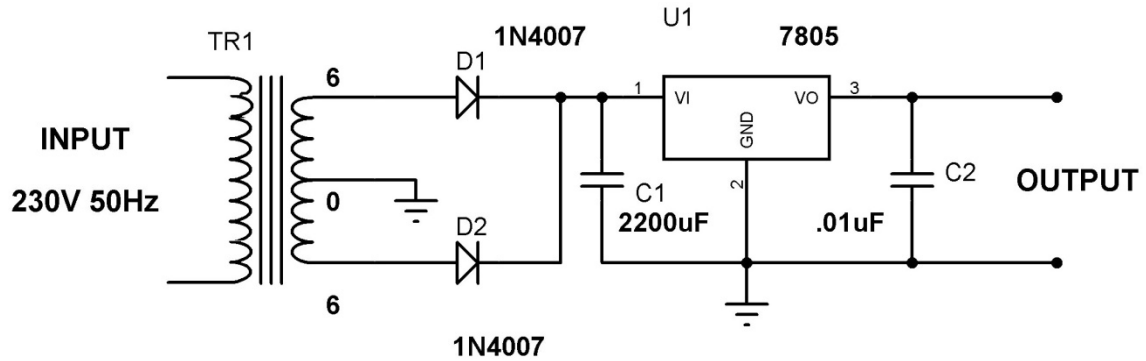


Figure 2.18: Crystal circuit

Source: www.electrosome.com (2013)

Crystal circuit will provide frequency to the microcontroller.

c.



**Figure 2.19:** Voltage regulator circuit

Source: [www.electrosome.com](http://www.electrosome.com) (2013)

Voltage regulator circuit is crucial to maintain a constant voltage 5V level to microcontroller and convert AC to DC voltage.

## 2.8 PROGRAMMING

Machine language is the only language that a controller can understand. The language consists of instructions in binary code that is specific to the particular process for which it is to be used. Every step that the controller needs to take must be written with instructions.

### 2.8.1 Boolean Flow Control

Boolean flow control makes the program behaves in a particular manner depending on the input given to the program. It is required since in a controller, not all parts are executed all of the time. Below shows a basic if-else, else-if Boolean flow control structure.

```
if (Condition1)
{
....
}
else if (Condition2)
{
....
}
else if (Condition3)
{
....
}
else
{
....
}
```

**Figure 2.20:** If-else-if control structure

Source: D’orazio, T.B. and Tan, H.H. (1999)

Program structure above shifts program control, step by step, through a series of statement blocks. Control stops at the relational expression that is true and executes the corresponding statement block. If none of the relational expressions condition 1, condition 2 and condition 3 are true, the final statement ‘else’ block is executed.

### 2.8.2 Operator

The operator is a relational expression that compares the values of two arithmetic expressions. It is a type of logical expression and produces a result of either true or false. In C programming, there are 6 relational operators shows in Table 2.1.



**Table 2.1:** C language relational operators

<b>Relational Operator</b>	<b>Meaning</b>
<	Less than
< =	Less than or equal to
= =	Equal to
>	Greater than
> =	Greater than or equal to
! =	Not equal to

Source: Striegel, A. and Rover, D. (2001)

## **2.9 RELEVANCE OF THE LITERATURE REVIEW**

The reviews help to generalize idea from the factual information that act as guidance towards the project. As for the conclusion of this chapter, understanding the theory and principles in hybrid air and pneumatic system is crucial to decide the design for this project. Basic circuit to build a microcontroller system is significant to proceed with this project as to achieve all the project objectives. Through it, common idea toward the methodological approach of the project can be obtained. Further details on the component selection and its general specification elaborate in Chapter 3.

## **CHAPTER 3**

### **METHODOLOGY**

#### **3.1 INTRODUCTION**

From the study made from various sources, idea, consideration and decision was made for the development of the engine control module for hybrid-air motorcycle. The decisions are as follows.

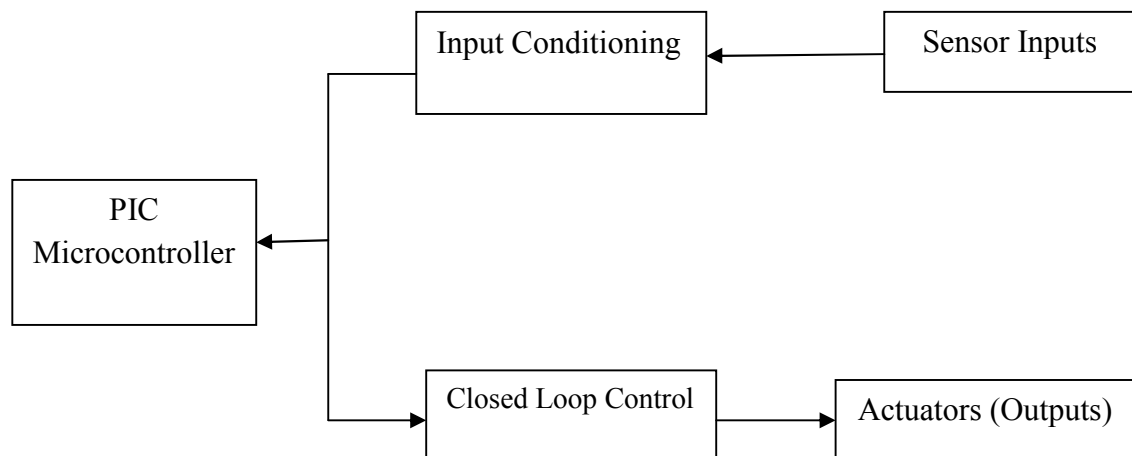
##### **3.1.1 Project Description**

The engine model that was used in this project is Subaru EA71 and it is a 4-stroke SI engine. In this project, a control module for air powered cylinder or air hybrid engine will be developed using the PIC microcontroller. Before the control system can be developed, the concept of how the engine will work needs to be known first. In air power cylinder, the piston only performs 2 strokes without ignition process. The compressed air will be injected into the cylinder through the air injector and provide force by high pressure to work on the piston.

##### **3.1.2 Design Concept and Criteria**

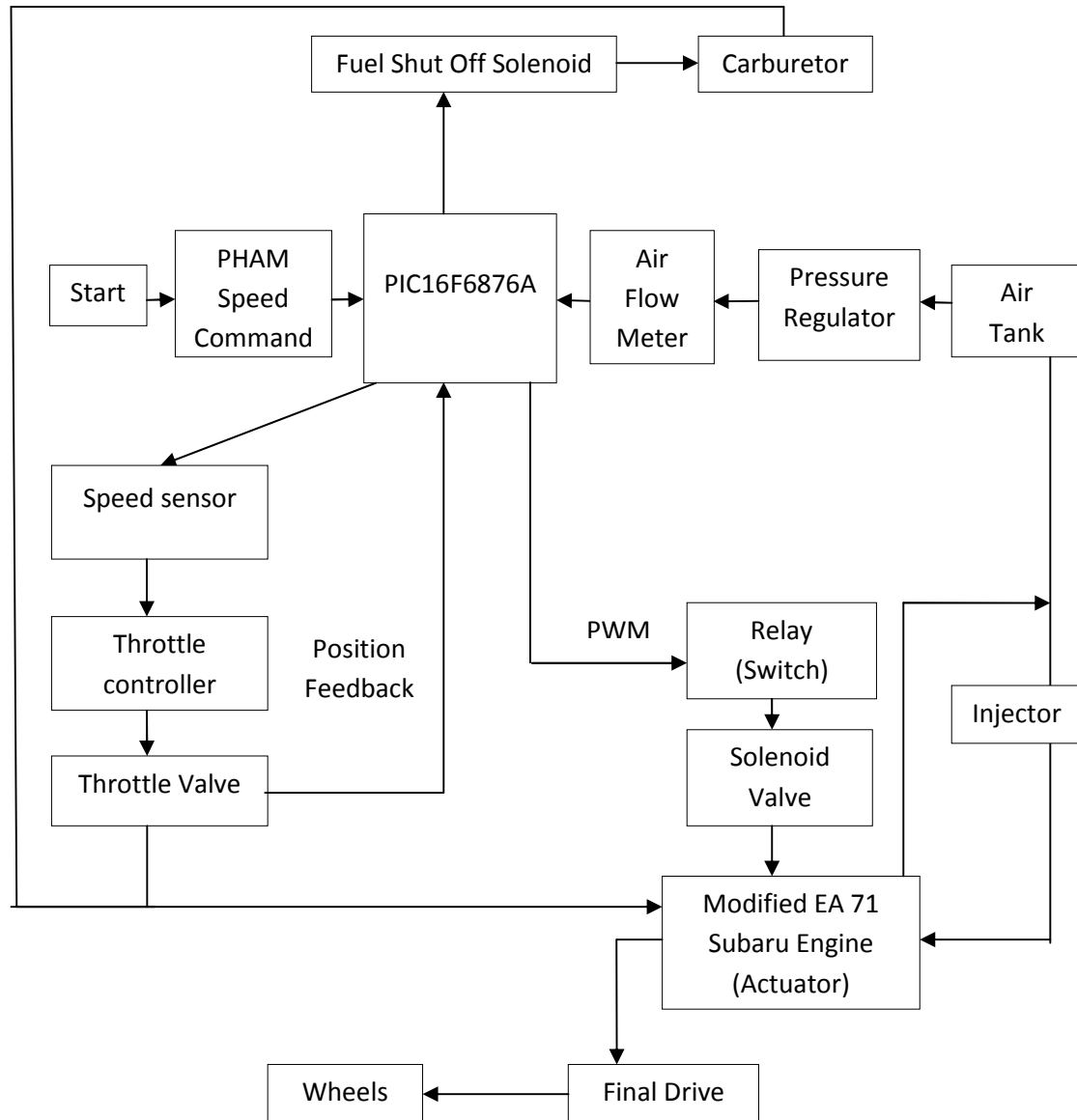
Engine control module or engine control unit is designed as a compact unit using PIC microcontroller as the main system, and to be applicable and directly installed into the motorcycle's engine. It contains a printed circuit board (PCB) with other electronic components. The control module should do as much as possible to minimize interface components. Pulse width modulation (PWM) will conduct the electrical current to a solenoid valve to adjust and regulate oil and air into the cylinder in meeting emissions

and performance requirements. Pulse width modulation (PWM) is done with a timer which has been programmed to control the output pulse width with the help of signal from the sensor involved. A multi terminal plug connects the engine system to its sensors, actuator, as well as to its power supply.



**Figure 3.1:** General control planning

### 3.1.3 Schematic Diagram of Plug-In Hybrid Air Motorcycle (PHAM) Control System



**Figure 3.2:** Schematic diagram of control system of plug-in hybrid air (PHAM) motorcycle

First of all, the main processor that controls the whole system is the PIC microcontroller, which is also known as a PIC management system. It works like an ECU that controls the operating modes, charging system of the compressed air tank and so on. Furthermore, it processes both analog and digital signals through a built in analog

to digital converter. Initially the Plug-In Hybrid Air Motorcycle (PHAM) runs only with normal engine mode. However, when the speed of the motorcycle was decreasing, the ICE engine will automatically cut off (air hybrid mode) to continue the cruise and recharge the compressed air in tank since a cylinder in the ICE engine was modified become a compressor.

The PIC will receive motorcycle speed feedback and speed command from the speed sensor located at the wheel of the motorcycle, and then it sends signal to the PIC microcontroller to be processed. From the PIC, analog signals will be sent to the controller of the ICE, thus controlling and regulating the fuel linkage by a fuel cutoff solenoid valve as an actuator. On top of that, different level of throttle command of driver triggers different mode of operation. Furthermore, PIC will receives feedback from the speed command, PHAM speed and compressed air tank pressure state to determine the type of operation to be used in propelling the PHAM. The PIC will change its operation mode according to those feedbacks and the PIC program coding.

## **3.2 MATERIALS SELECTION**

### **3.2.1 PIC Microcontroller (PIC16F876A)**

PIC microcontrollers are usually used in automatically controlled products and devices such as automobile engine control systems, remote controls, office machines, appliances, power tools and many more. To summarize, a PIC16F876A microcontroller has been chosen to use in this project because in terms of its size, cost, and power consumption compared to a design using other microprocessor, memory, and input/output devices, PIC16F876A microcontrollers make it economical to electronic control many more electrical and mechanical devices. The other features are stated below:

- a. 8kb Internal Flash program memory
- b. Operating Speed at 10MHz
- c. Direct In-Circuit Programming for Easy Program Updates
- d. Up to 28 I/O points with easy to connect standard headers

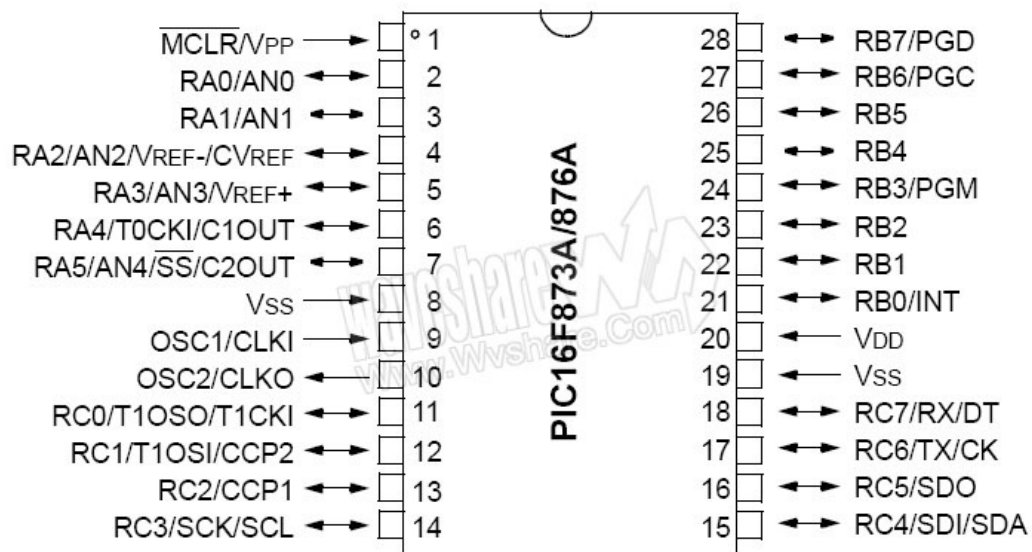
- e. 25mA sink/source per I/O
- f. Internal EEPROM
- g. 8 Channel 10-bit A/D Converter
- h. One 16-bit Timer with Two 8-bit Timers
- i. Serial port
- j. Reset Button



**Figure 3.3:** PIC16F876A

Source: [www.wvshare.com](http://www.wvshare.com) (2013)

## 28-Pin PDIP, SOIC, SSOP



**Figure 3.4:** PIC16F876A datasheet preview

Source: [www.wvsahre.com](http://www.wvsahre.com) (2013)

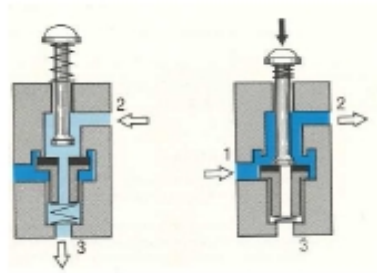
### 3.2.2 Solenoid Valve

In a pneumatic system, valve is a device that controls the flow direction and pressure of compressed air. Valve is important to regulate the amount of the compressed air to supply to the actuator. There are various types of valves. In terms of function, it can be classified into:

- Directional control valves: Control the flow direction of compressed air
- Non-return valves: Allow the flow of compressed only in one direction.
- Pressure control valves: Limit the pressure of compressed air supplied.
- Flow control valves: Restrict the compressed air to reduce its flow rate.

However, this project only concern on directional control solenoid valves since the main components of this project are utilizing electrical signal to control flow of compressed air and movement of the actuator. In this project, an on/off valve such as solenoid valve will be used as to control and regulate the air into the compressed air

tank. The valve used in this project is 3/2 valves where the drain port 3 has been sealed and therefore operates as a 2/2 valve. It is important to note that in Figure 3.5 shows a valve that opens or closes by pressing a button. The concept of the solenoid valve is same but they are activated when a current is used.



**Figure 3.5:** Normally closed 3/2 valve

Source: Maisam Jeddi Tehrani (2008)

### 3.2.3 Fuel Shut Off Solenoid Valve

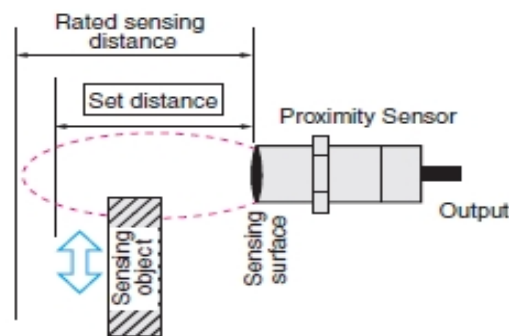
As stated before in the solenoid valve section, an on/off valve such as solenoid valve will be used as to control and regulate the air into the compressed air tank. Another type of solenoid valve that has been used in this project is fuel shut off solenoid valve, where its function is to regulate the flow of fuel depends on activated mode at that time. This valve is normally closed and it will open when current is supplied from the battery through a switch.

### 3.2.4 Sensor

In order for the PIC microcontroller to recognize the speed of the vehicle, proximity sensor has been used for that purpose. An electronic proximity sensor actually is an inductive sensor which its function is to detect metallic objects without touching them through an electromagnetic field. Therefore, it is very suitable to detect the speed of an object. To detect the speed of the hybrid air motorcycle, it will be mounted to the wheel where it is used to detect a piece of metal that being mounted onto



the rim as well. Due to the characteristic of the sensor that it only able to sense up to a certain distance of limit, calibration must be done so that it sense only on the surface of the mounted metal. Whenever the wheel turns by one round, the sensor detects it and send signals to the PIC microcontroller. On top of that, PIC microcontroller will convert the analog signal to digital signal from the sensor and the result which is the speed in terms of RPM will be displayed on the LCD.

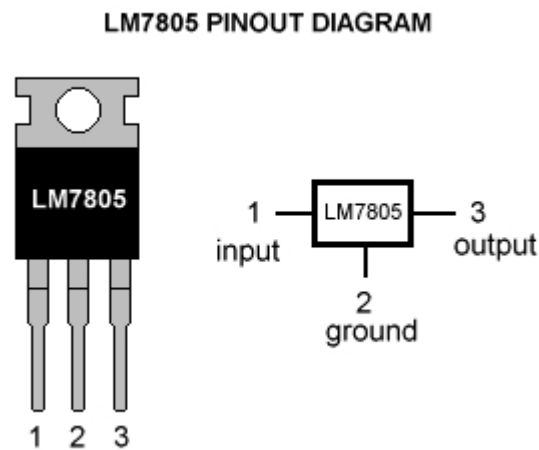


**Figure 3.6:** Proximity sensor operation

Source: [www.Omron-ap.com.my](http://www.Omron-ap.com.my) (2013)

### 3.2.5 Voltage Regulator

In order to connect the voltage of the power sources such as battery to the PIC controller, a voltage regulator has been used where the function of voltage regulator is to maintain a constant voltage level. This is mainly due the input voltage rating at the PIC microcontroller digital input port is only 5VDC, while the voltage from the battery is 12V. The voltage regulator IC used in this project is LM7805 where it has three pins which are input, output and ground. This device can support an input voltage anywhere from a couple of volts over the intended output voltage, up to a maximum of 35 to 40 volts depending on the make, and typically provide 1 or 1.5 amperes of current.



**Figure 3.7:** LM7805 voltage regulator

Source: [www.electrosome.com](http://www.electrosome.com) (2013)

### 3.2.6 Relay

In order to control the on off states of the solenoid valve and other actuator, a relay switch must be used since it is a simple electromechanical switch consists of an electromagnet and a set of contacts that can perform on and off function like a switch when a current flows through the magnetic coil inside. Furthermore the PIC microprocessor's maximum digital output voltage only 5V, where the actuators require 12v, therefore a relay that is connected to 12V of battery can be used to achieve the this objective. The relay that has been used in this project is Songle SPDT Relay SRD 05V where it is a simple relay magnetic circuit to meet low cost of mass production and it can been used for domestic appliance, office machine, audio, equipment, automobile and many more.



**Figure 3.8:** Songle SPDT relay SRD 05V

Source: cytron.com.my (2013)

### 3.2.7 USB PIC Programmer

UIC00B is used due to this hardware is essential to flash the program that has been made in the MikroC software or other C compiler software into the PIC microcontroller. Besides flashing 8bit PIC, it can also program 16bit and 32bit PIC. On board ICSP (In Circuit Serial Programming) connector also offers flexible methods to load program. It is very convenient to use for flashing program into PIC because it uses only a USB cable which can be found in almost all computer.



**Figure 3.9:** USB PIC programmer

### 3.2.8 Liquid Crystal Display (LCD)

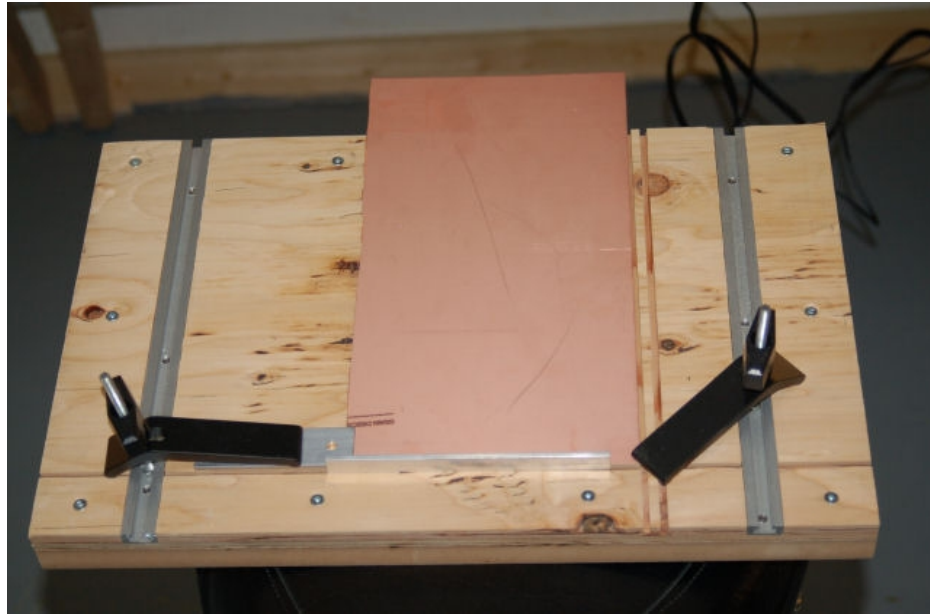
To show the value of speed in terms of RPM, an LCD has been used for that objective. Recently a lot of projects using this intelligent LCD because of their ability to display just not numbers, but also letters, words and all types of symbols. Even limited to character –based modules, but there is still a wide variety of shapes and size available. The LCD's dimension used in this project is 16 X 2 which is it can display up until 16 letters or words.



**Figure 3.10:** 16 X 2 LCD

### 3.2.9 Printed Circuit Board (PCB)

Printed circuit boards that have been used in this project are primarily an insulating material used as the base, in which conductive strips are printed. The base material is generally fiberglass, and the conductive connections are generally copper and are made through an etching process. PCB board design defines the electrical pathways between components and it is derived from a schematic representation of the circuit. After it is derived or imported from a schematic design, it translates the schematic symbols and libraries into physical components and connections. The forward section in this chapter will show on how the PCB was customized using the Proteus software and CNC milling machine through a technology that called Through Hole Technology (THT).



**Figure 3.11:** Printed circuit board

### **3.3 SOFTWARE**

#### **3.3.1 MikroC**

MikroC is a powerful, feature rich development tool for PIC microcontroller. It is designed to provide the customer with the easiest possible solution for developing applications for embedded systems, without compromising performance or control. MikroC provides a successful match featuring highly advanced Integrated Development Environment (IDE), ANSI compliant compiler, broad set of hardware libraries, comprehensive documentation, and plenty of ready-to-run examples.

PIC and C fits together well where PIC is the most popular 8-bit chip in the world, used in a wide variety of applications, and C, prized for its efficiency, is the natural choice for developing embedded systems. It develops applications quickly and easily with the world's most intuitive C compiler for PIC Microcontrollers (families PIC12, PIC16, and PIC18). Highly sophisticated Integrated Development Environment (IDE) provides the power which is needed with the simplicity of a window based point-and-click environment. With useful implemented tools, many practical code examples,

broad set of built-in routines, and a comprehensive help, MikroC makes a fast and reliable tool. MikroC allows developing and deploying complex applications:

- a. C source code using the highly advanced Code Editor.
- b. Use the included MikroC libraries to dramatically speed up the development like data acquisition, memory, displays, conversions, communications and so on.
- c. Monitor program structure, variables, and functions in the Code Explorer.
- d. Generate commented, human-readable assembly, and standard HEX compatible with all programmers.
- e. Inspect program flow and debug executable logic with the integrated debugger.
- f. Get detailed reports and graphs on code statistics, assembly listing, calling tree and many more.

For all reasons above, the MikroC software will be used so that a programming structure can be developed in this project.

### **3.3.2 PICKit 2 Programmer**

The programming that was finished and build by using MikroC will be used later on PICKit 2 programmer for the burning process. PICKit is a family of programmers for PIC microcontrollers made by Microchip Technology. They are used to program and debug microcontrollers. The PICKit 2 has a programmer-to-go (PTG) feature, which it can download the hex file and programming instructions. PICKit 2 programmer can support a maximum up to 4M bytes of memory for programmer-to-go feature. It is also can support other devices or microcontroller from other family including PIC32 and Microchip serial EEPROM products. Windows application for the PICKit 2 programmer provides a simplified and feature rich interface to make it easy to use.

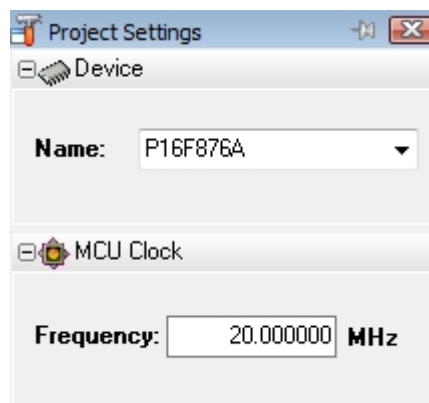
### **3.3.3 Proteus Professional**

Schematic design of the circuit is the hardest part in the process of creating a PCB layout. To overcome this problem, Proteus Professional software has been used in

this project to develop the circuit schematic design and the printed circuit board (PCB) layout. With this software, there were contains two sub software which are ISIS and ARES, where in ISIS; the schematic design of the circuit was designed manually after all consideration was met, whereas in ARES, the PCB layout will be developed. Using ISIS and ARES together guaranteed to produce a PCB layout which matches the schematic exactly. Besides, it is offering automation of both component placement and track routing, getting the design into the computer can often be the most time consuming element of the exercise.

### 3.4 PROGRAMMING DEVELOPMENT

For the next step which is programming part, MikroC software has been used to write and build the program, as stated in the previous chapter. The first thing before can start the programming is to define what type of PIC microcontroller that will be used until the end of the programming. In this project, PIC16F876A has been used and for the frequency of the MCU clock, it has been set to 20 MHz, depends on what type of crystal oscillator that has been used.



**Figure 3.12:** Project settings

In the first line on programming page, the directives of the programming must be defined by the use of `#define` words. It is depending on how many parameters to be defined, but for this project, the parameter that has been defined is auto, hybrid and fuel mode only.

```

• #define      AUTO      1
• #define      HYBRID    2
• #define      FUEL      3

```

**Figure 3.13:** Directive define

The next line in the programming page is to define the global and constant that will be used. The function of it is in the registry and their bits are implicitly declared as global variables. These identifiers have an external linkage, and are visible in the entire project. In this programming, the connection for each of the LCD pins with the PIC16F876A will be defined.

```

- // LCD module connections
• sbit LCD_RS at RC3_bit;
• sbit LCD_EN at RC2_bit;
• sbit LCD_D4 at RC4_bit;
• sbit LCD_D5 at RC5_bit;
10 sbit LCD_D6 at RC6_bit;
• sbit LCD_D7 at RC7_bit;
•
• sbit LCD_RS_Direction at TRISC3_bit;
• sbit LCD_EN_Direction at TRISC2_bit;
- sbit LCD_D4_Direction at TRISC4_bit;
• sbit LCD_D5_Direction at TRISC5_bit;
• sbit LCD_D6_Direction at TRISC6_bit;
• sbit LCD_D7_Direction at TRISC7_bit;
• // End LCD module connections
20
• sbit PB1 at RB0_bit;
• sbit PB2 at RB5_bit;
• sbit PB3 at RB4_bit;
• sbit LED1 at RA1_bit;
- sbit LED2 at RA2_bit;
• sbit LED3 at RA3_bit;
•
• unsigned int RPM;
• unsigned char mode;

```

**Figure 3.14:** Globals and constant defining

After the global and constant module have been defined, the next line is to create the void function. Void function is a special type indicating the absence of any value. There are no objects of void but instead, void is used for deriving more complex types. Void function also can be used as a function heading if the function does not take any



parameters. In this programming, void function has been used to display the RPM value. It is also used to define the main programming from starting until the end.

```

• void DisplayRPM(void)
• {
•     Lcd_Chr(2,6, ('0'+(RPM/1000)%10));
•     Lcd_Chr(2,7, ('0'+(RPM/100)%10));
•     Lcd_Chr(2,8, ('0'+(RPM/10)%10));
•     Lcd_Chr(2,9, ('0'+(RPM/1)%10));
• }
•
• void main()
40 {
41     ADCON1 = 0x0E;
•     TRISA = 1;
•     PORTA = 0;
•     TRISB = 255;
•     PORTB = 0;
•     mode = AUTO;
•
•     Lcd_Init();                // Initialize LCD
•     Lcd_Cmd(_LCD_CLEAR);      // Clear display
•     Lcd_Cmd(_LCD_CURSOR_OFF); // Cursor off
50     Lcd_Out(1,1,"AirHybridEngine"); // Write text in first row
•     Lcd_Out(2,1,"RPM:");
•     Delay_ms(500);

```

**Figure 3.15:** Void functions

For this project, 145 lines had been used to complete the writing of the total programs. Before it can be burned into the PIC16F876A by using USB programmer, the programming must be built first so that the errors or the wrong typing in the programs can be detected. If no errors occur, the programming was ready to burn into the PIC16F876A later. The programs that had been build was automatically saved in the .hex file because this file will be used in simulation and burning process. The full programming is shown in APPENDIX C.

Messages Quick Converter			
Errors Warnings Hints			
Line	Message No.	Message Text	Unit
0	1	mikroC PIC1618.exe -MSF -DBG -p16F876A -DL -O111111114 -fo20 -N'D:\PSM\Hybrid Simulation (P...	
0	1501	Specified search path does not exist: 'F:\Hybrid Simulation (PIC16F873A) dep 50'	
0	1501	Specified search path does not exist: 'E:\FYP 2013 UMP\Hybrid Simulation (PIC16F873A) dep 50'	
0	1139	Available RAM: 352 [bytes], Available ROM: 8192 [bytes]	
0	126	All files Preprocessed in 719 ms	
0	122	Compilation Started	Hybrid Simulation.c
144	123	Compiled Successfully	Hybrid Simulation.c
0	127	All files Compiled in 453 ms	
0	1144	Used RAM (bytes): 91 (26%) Free RAM (bytes): 261 (74%)	Used RAM (bytes): 91 (26%) Free RAM (bytes): 261 (7...
0	1144	Used ROM (program words): 915 (11%) Free ROM (program words): 7277 (89%)	Used ROM (program words): 915 (11%) Free ROM (pro...
0	125	Project Linked Successfully	Hybrid Simulation.mcppi
0	128	Linked in 2016 ms	
0	129	Project 'Hybrid Simulation.mcppi' completed: 3781 ms	
0	103	Finished successfully: 11 Jun 2013, 10:54:05	Hybrid Simulation.mcppi

**Figure 3.16:** Error window

### 3.5 CIRCUIT DEVELOPMENT AND SIMULATION

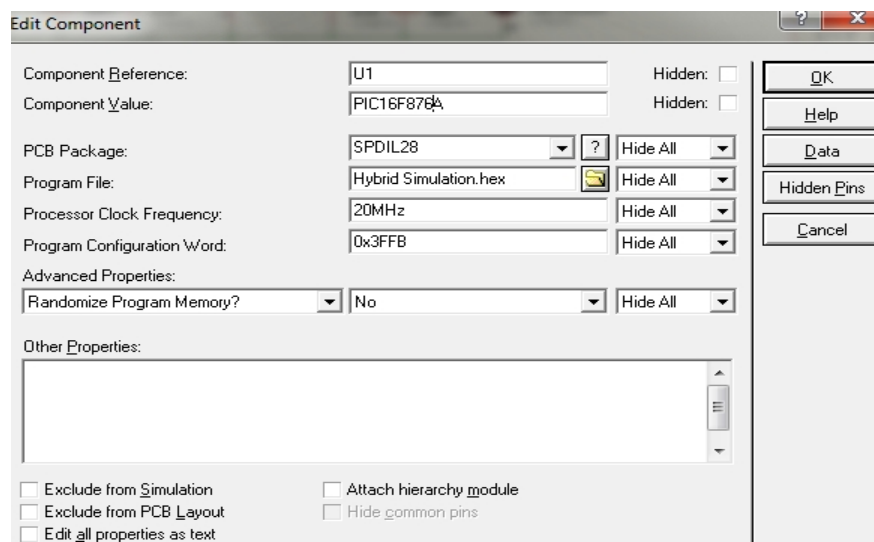
After the programming was developed, at the same time the circuit design was developed using Proteus Professional software. With this software, there were two sub software which is Intelligent Schematic Input System (ISIS) and Advanced Routing and Editing Software (ARES), where in ISIS; the schematic design of the circuit was designed manually after all consideration was met, whereas in ARES, the PCB layout had been developed and the components also was placed manually.

The design of the circuit had been started with taking and listing down all the components needed to be interfaced later. These components were taken from the devices library manager and it can be chosen freely and widely because there are lots of components that available.



**Figure 3.17:** Devices picked from the device library manager

The devices that have been picked were put manually on the ISIS layout and they were arranged nicely to make it easy to understand and modified later. For the fully schematic design and PCB design layout, it can be seen in the APPENDIX D. After all of devices were put and arranged together, the .hex file in the programming part in previous section will be used for the simulation purpose.



**Figure 3.18:** .hex file used for simulation purpose

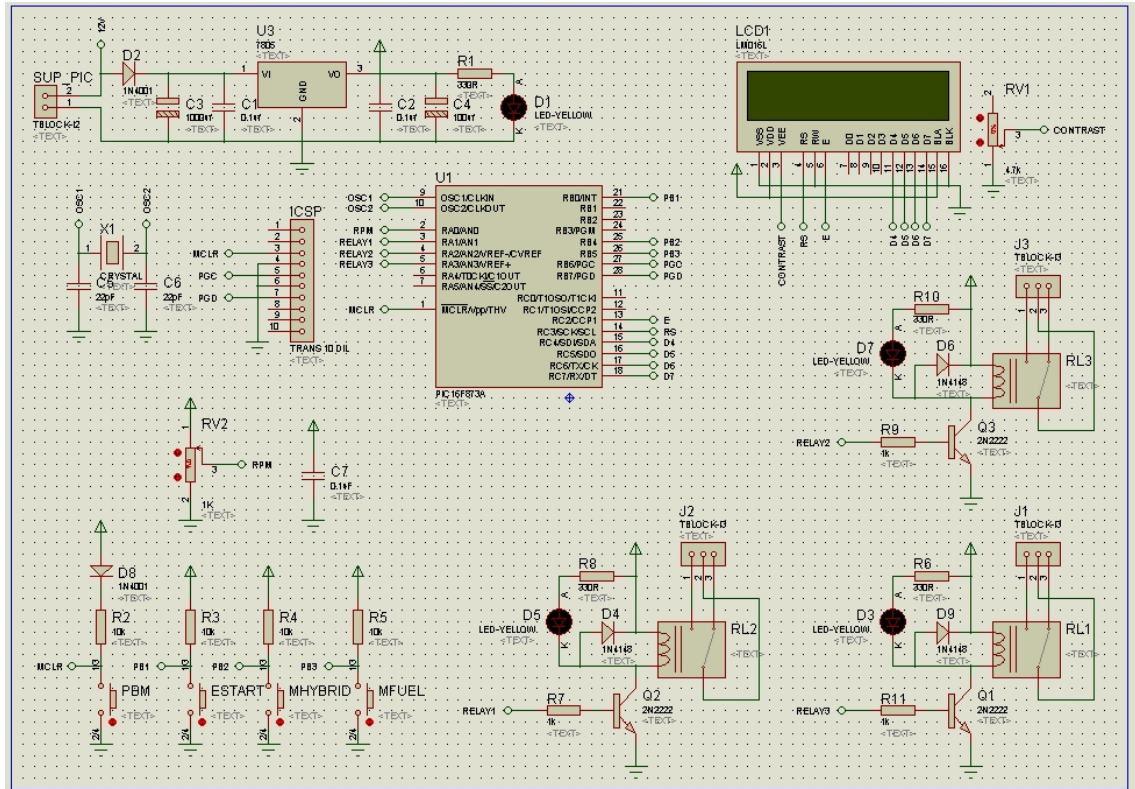
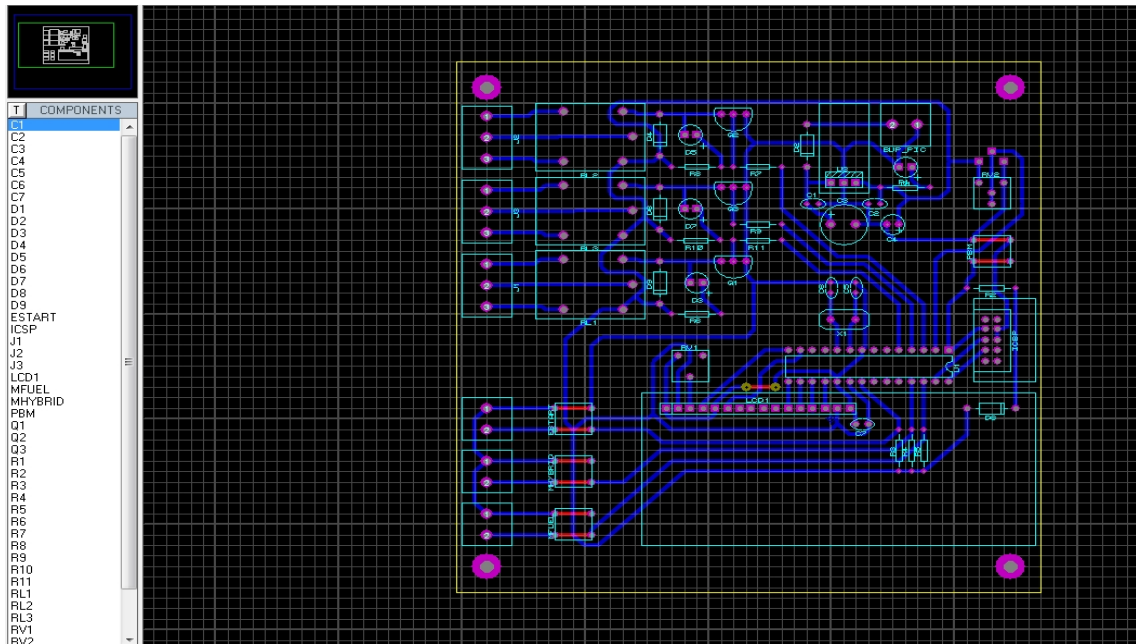


Figure 3.19: Schematic circuit design

### 3.6 PRINTED CIRCUIT BOARD (PCB) DEVELOPMENT

For producing PCB layout drawings, the ARES has been used for that purpose. All of the components from ISIS design were imported to ARES and the components will be listed in a component box. Each of the components was placed manually on board edge that has been drawn. For the routing process, the circuit design must be routed manually although in the ARES have the option for the auto router. This is because the auto router function is most likely to use in double layer PCB design, therefore auto router is not recommended for routing the single layer PCB design.



**Figure 3.20:** PCB layout design

As was mentioned before this in materials selection section, the PCB will be developed by using a technology namely Through Hole Technology (THT). There are two famous ways that can be applied in PCB's development such as Through Hole Technology (THT) and Surface Mount Technology (SMT), but what distinguishes both these technologies is their ability to produce a consistently high quality PCB quickly and efficiently, and also in terms of component packaging. THT was chosen in this project because it is more suitable for the electronic hobbyist due to the easy fabrication process and easy to get its components in the market compared with SMT that usually applied in the electronics industry for more complex circuit design.

Before that, the circuit design can be drawn using Proteus Professional software. This allows individual components such as resistors, integrated circuits and capacitors to be dragged onto the screen and connected together in forming a complete circuit. The finished circuit can then be simulated on screen. If the circuit is not correct or something wrong with the connection, it can be altered until it works in the desired way. This will allow user to test the circuit to the computer and correct any mistakes or make improvements. This will save time as there is no need to build the circuit with real components.

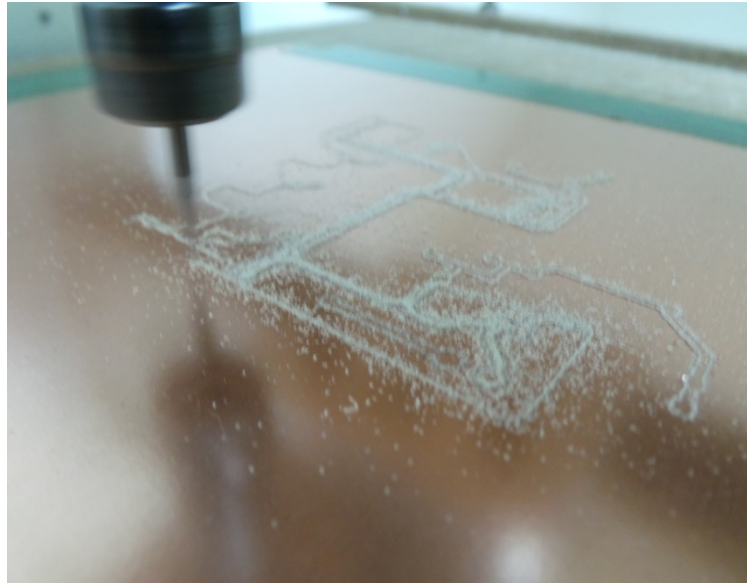
The next process is the PCB fabrication process that can be started by using a board is made from glass reinforced plastic with copper tracks in the place of wires. The components are fixed in position by drilling holes through the board before locating the components and then soldering them in place. The copper tracks link the components together in forming a circuit.

Once the circuit has been designed and simulated, the completed circuit is ready for export to other software namely Mach3, that will be operated by CNC milling machine later. The generated output file from the Proteus Professional must be saved in different file extension, called a part program. The part program is often written in “GCode,” that describes the machine steps required to make the desired part. The file then will be transferred using medium such as USB flash drive to a machine controller. The machine controller will reads and interprets the part program to control the tool which will cut the workpiece. By using Mach3 software that's running on a PC or a laptop, it will perform the machine controller function and send signals to the Drives where the signals from the machine controller are amplified by the Drives so they are powerful enough and suitably timed to operate the motors driving the machine tool axes. Finally, the axes of the machine are moved by screws, racks or belts which are powered by servo motors or stepper motors.

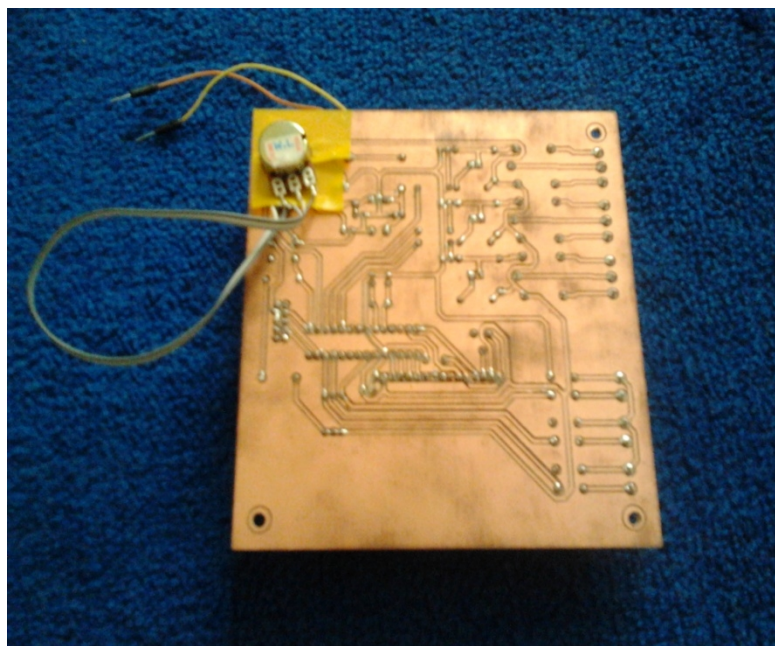


**Figure 3.21:** CNC milling machine





**Figure 3.22:** Drilling process



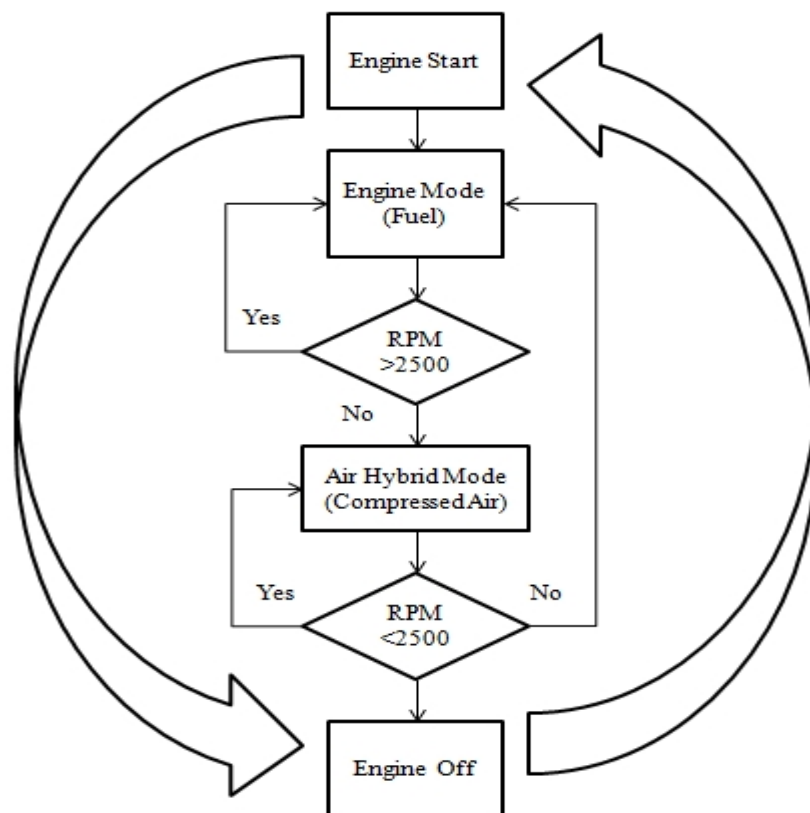
**Figure 3.23:** Bottom/Copper side of PCB

## CHAPTER 4

### RESULT AND DISCUSSION

#### 4.1 DESIGN ALGORITHMS

After all consideration and expectation was met, the final concept and design has been decided. Before the control module can be fabricated, the algorithms of the design must be stated clearly. The algorithms are as shown below:



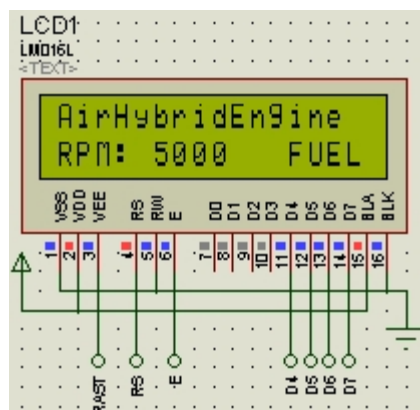
**Figure 4.1:** Design algorithms



As shown in Figure 4.1, the user or rider will enter the command which is to start the engine and at the first stage, the hybrid air motorcycle will run on the normal engine mode that used gasoline as usual, or known as auto mode. The estimated range of speed of the modified Subaru EA-71 boxer engine is around 2500 RPM to 5000 RPM. The speed of the engine cannot be zero when the ignition was started and at this stage it was called engine idle state where the speed at this time is around 1000 RPM. When it speeds down below than 2500 RPM, user or rider may have an option whether want to stay on engine mode or to switch the air hybrid mode because it can help to reduce the use of fuel. Which at this stage is the second stage, the high pressure compressed air from the air compressed tank will be injected into the cylinder through an injector and at the same time, the charging process of the air in the tank will occur, or known as charging mode. All these processes are the continuous process and for the result, it can give an optimum ride to the rider.

## 4.2 SIMULATION RESULT

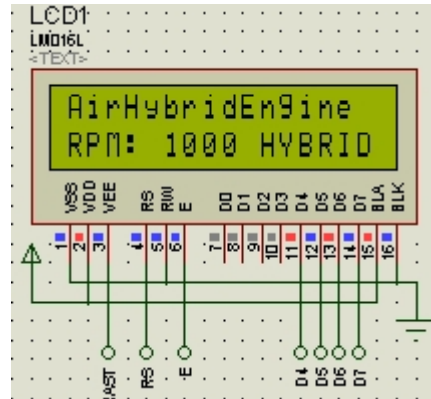
The results from the simulation are shown below for each mode of operation of the air hybrid motorcycle.



**Figure 4.2:** Normal engine mode (gasoline)

When the speed is more than 2500 RPM, the air hybrid motorcycle will use the normal engine mode that uses gasoline as power sources. At this point of mode, the fuel shut off solenoid valve will be in off state which is mean the valve is in open state while

for the solenoid valve that regulate and control the air in compressed air tank, it will be in on state which is means the valve is in close state.

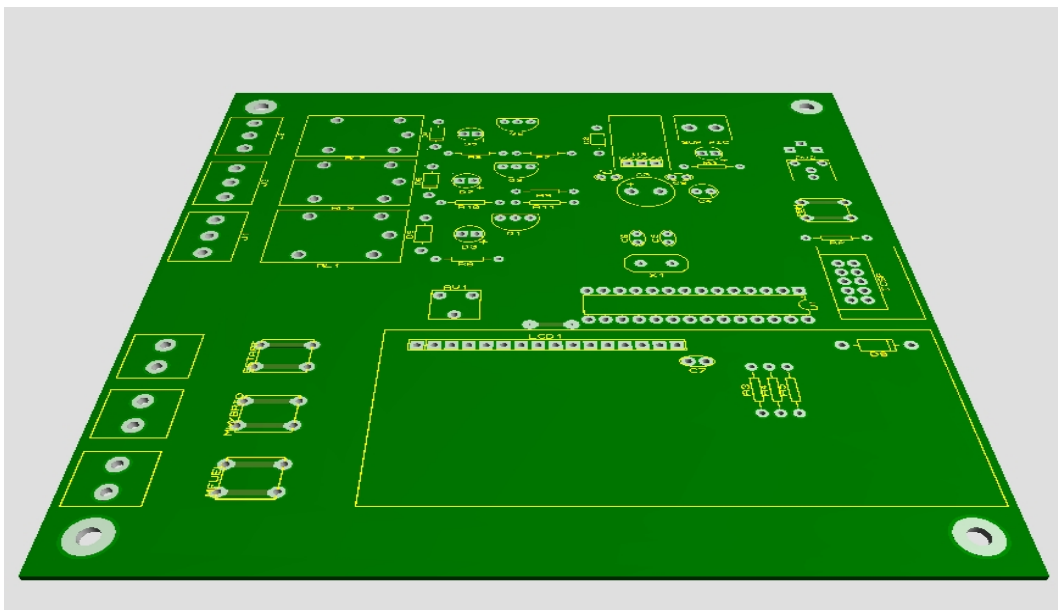


**Figure 4.3:** Air hybrid mode (compressed air)

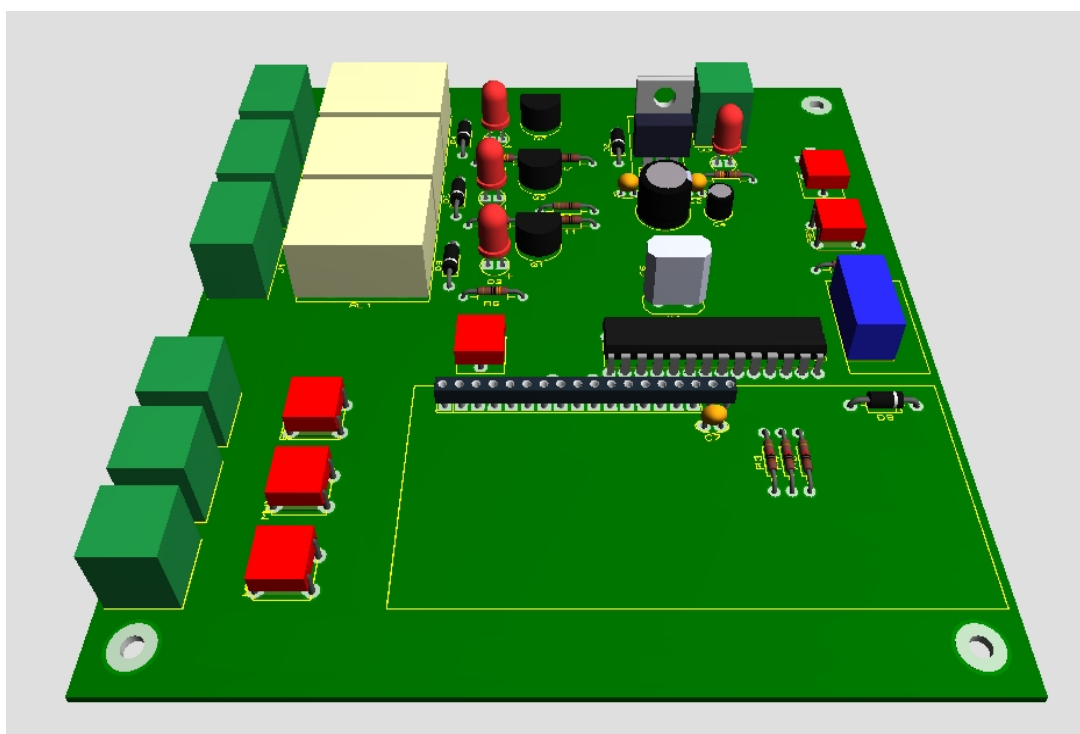
In Figure 4.3, it shows the air hybrid mode when the speed of the air hybrid motorcycle is less than 2500 RPM, where it will use the high pressure compressed air from the air storage that will be injected into the cylinder. At this point of mode, the fuel shut off solenoid valve will be in on state which is mean the valve is in close state while for the solenoid valve that regulate and control the air in compressed air tank, it will be in off state which is means the valve is in open state so that air can be injected through an injector to move the actuator which is piston in engine cylinder.

### 4.3 3D VISUALIZATION ON PCB CIRCUIT

The fully design of PCB layout can be seen in 3D view before the real prototype can be developed. By using the 3D visualization tool in ARES, it will provide a way to extrude a layout and view the board as it would appear in real life. This is extremely useful as a design aid during board layout. Beside, the user can also specify a height plane corresponding to the board chassis which will appear as a semi-transparent box around the board, allowing for a quick visual check for protrusions. The 3D visualization on the circuit with component and without component is shown below.



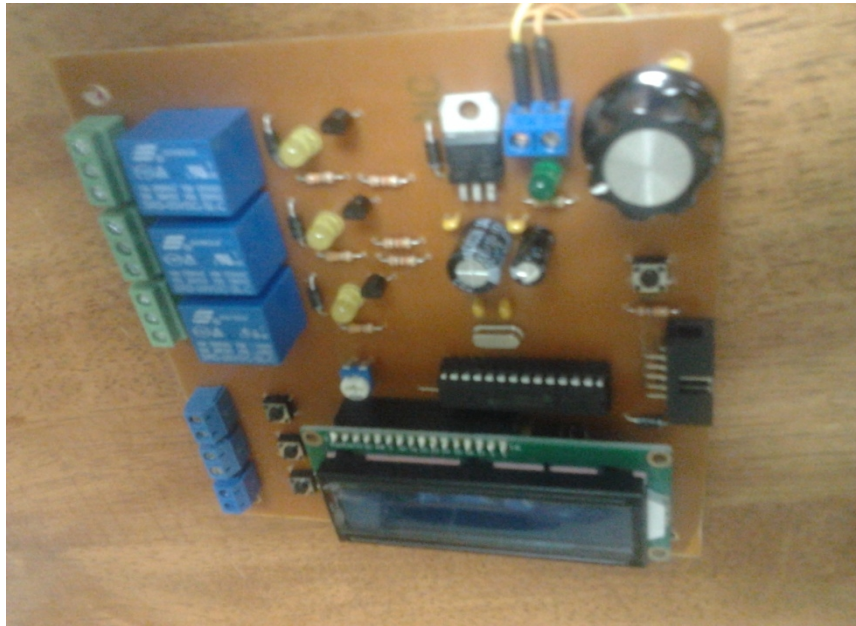
**Figure 4.4:** 3D visualization (without component)



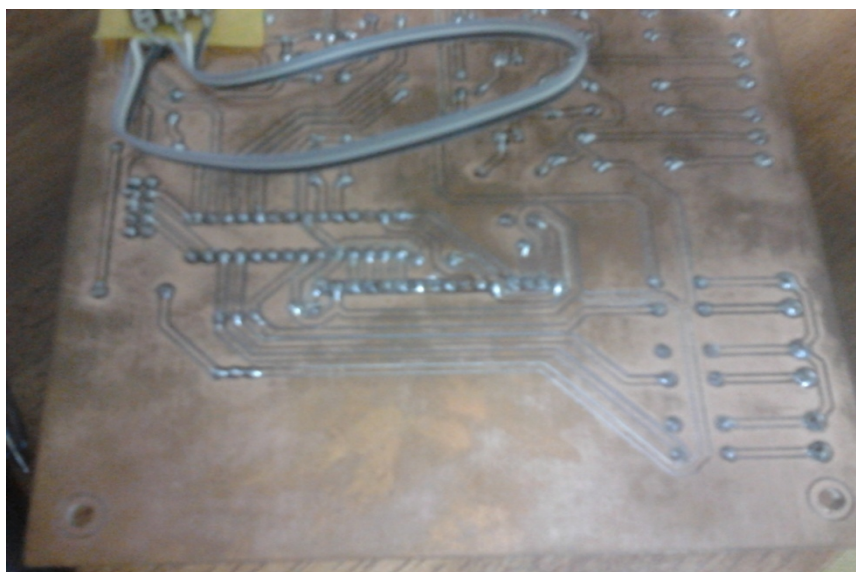
**Figure 4.5:** 3D visualization (with component)

#### 4.4 FINAL CIRCUIT

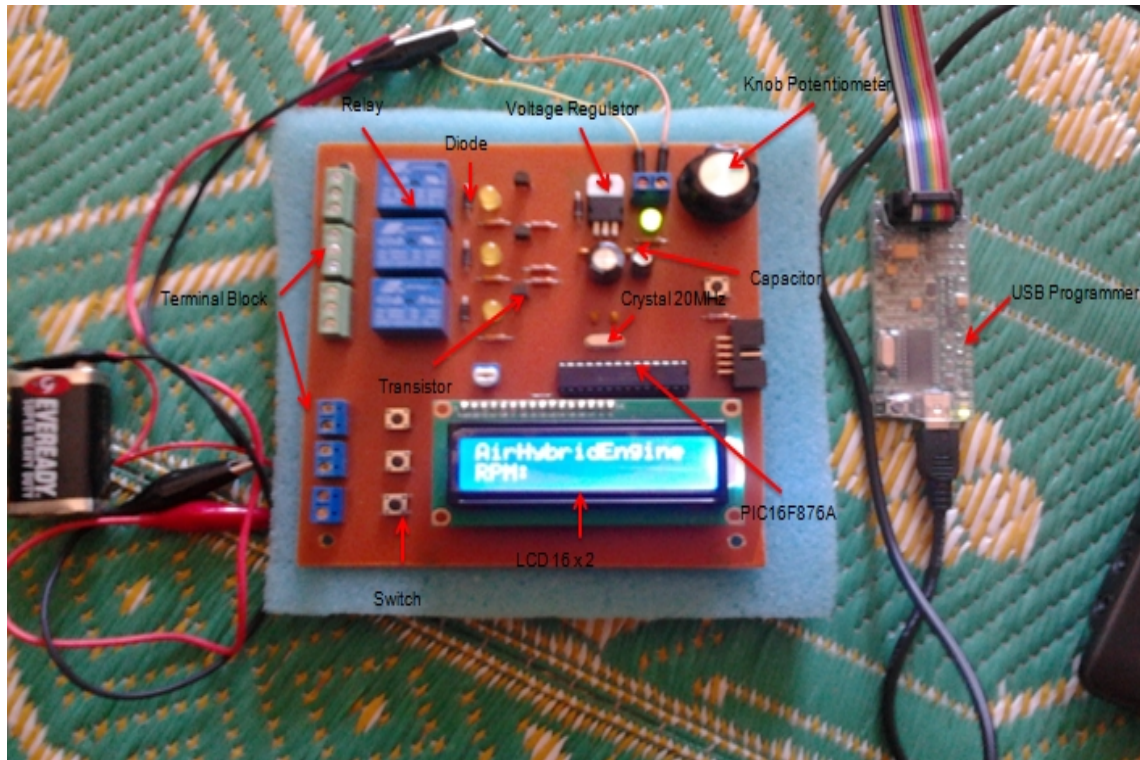
During the assembly process, all components of the control module were placed on the PCB according to the assembly sequences. The sequences consist of components fitting and the soldering process.



**Figure 4.6:** Components fitting



**Figure 4.7:** Soldering process



**Figure 4.8:** Final circuit

#### 4.4.1 Modes of Operation

As stated before, this control module will have different modes of operation such as auto mode, normal engine mode, air hybrid mode and charging mode. The user or rider will enter the command which is to start the engine and at the first stage, the hybrid air motorcycle will run on the normal engine mode that used gasoline as usual, or known as auto mode. The estimated range of speed of the modified Subaru EA-71 boxer engine is around 2500 RPM to 5000 RPM. The speed of the engine cannot be zero when the ignition was started and at this stage it was called engine idle state where the speed at this time is around 1000 RPM. When it speeds down below than 2500 RPM, user or rider may have an option whether want to stay on engine mode or to switch the air hybrid mode because it can help to reduce the use of fuel. Which at this stage is the second stage, the high pressure compressed air from the air compressed tank will be injected into the cylinder through an injector and at the same time, the charging process of the air in the tank will occur, or known as charging mode.





**Figure 4.9:** Circuit in state “ON”



**Figure 4.10:** Auto mode



**Figure 4.11:** Normal engine mode



**Figure 4.12:** Air hybrid mode

## 4.5 CALCULATION

### 4.5.1 Resistor Circuit

The resistor circuit will drive a relay coil from a low power output from PIC16F876A. It is used to switch high loads or loads that need AC current to operate. The relay will be actuated when the input of the circuit goes high. The protection diode Dp is used to protect the transistor from the reverse current generated from the coil of the relay during the switch off time. The values for Rb and Qs vary accordingly. The way to calculate them is by using the equation from Chapter 2.

The output from PIC16F876A is required to operate a relay with a 70 Ohm coil. The supply voltage is 9V for the transistor and 5V for the PIC. The PIC can supply a maximum current of 4mA. The calculation is shown below:

$$I_L = V_S / R_L \Rightarrow I_L = 10 / 70 = 128\text{mA}$$

The transistor must have an  $h_{FE}$  greater than  $5 \times 128 / 2 \Rightarrow h_{FE} > 320$ . Hence, the suitable transistor that can be chosen is with  $h_{FE} \Rightarrow 320$  and  $I_C \Rightarrow 128\text{mA}$ . The transistor that has been used in this project is 2N2222, where the value for the  $h_{FE}$  is around 350 and the value of  $I_C$  is around 600mA.

For the  $R_B$  resistor, the calculation was different because the power supplies of transistor and  $I_C$  are different; hence the second formula was used:

$$\begin{aligned} R_B &= (V_{CC} \times h_{FE}) / (5 \times I_L) \\ R_B &= (9 \times 320) / (5 \times 0.128) \\ &= 4500 \text{ Ohm} \\ &= 4.5 \text{ K Ohm} \end{aligned}$$

The closest resistor possible to this value can be chosen for this circuit. The protective diode that suitable for this circuit could be the 1N4148 or any general purpose diode.



#### **4.6 BILL OF MATERIALS**

From the material consideration, a bill of material is created as a guide in the development process. The bill of materials consists the quantity of each component, the value of the components, the references to components, and also their order code. The total part listed on the bill of material is forty eight and can be referred in Appendix B.

## **CHAPTER 5**

### **CONCLUSION AND RECOMMENDATIONS**

#### **5.1 CONCLUSION**

This chapter will conclude the development of this project. The outcome of the project will be related to the scope and objective of the project. From that, the project will be determined whether its objective is achieved or not. This chapter was outlined to begin with conclusion followed by recommendations for future work. In consequence of this thesis, it was noticed that air hybrid engine technology and researches are still new and very limited especially in this country. Hence, a literature review was focused on the studies which were continuing in abroad. Most of them were about the air hybrid technology and how that technology can be controlled. In this thesis work, a control algorithm and an electronic control module were designed and a prototype circuit was developed. They were designed and developed to achieve understanding in principle of renewable energy that not possible to use widely in the future.

In this thesis, a control module was designed, implemented and programmed to automate the some number of parameters. To achieve the objective in this project, a control system was developed using a microcontroller. It was used to control almost all automated processes. A microcontroller can be used to perform almost any function. Although it is small, relatively cheap and reliable, but more importantly replacing it with a similar system built from discrete components would involve a very difficult and complex design task.

In the design and development of the control module, it proved that technology and engineering is not only can be learned using the theoretical method but also can be

learned using a practical approach without compromising theoretical knowledge. As for an overall conclusion for the development of extended range and blended control module for plug-in hybrid air motorcycle, the control module does not manage to be tested because of several such as cost constraint, time constraint and problem regarding the engine.

## **5.2 RECOMMENDATIONS**

For future development of this project, some recommendation can be proposed in this thesis. This project should be continued by another student for further research and developments such as a system that can control more parameters in the engine and much more.

### **5.2.1 Testing**

In this project the real testing process with the engine is not done because of time limitation and problems with the engine itself. Several testing mechanisms can be used to the control module functionality. Several ideas of method and process of testing have been pointed to test the control module. This is including:

- a. Testing with other engine: To ensure the control module can be function properly, it can be tested at another engine that work well so that all problems that may arise can be identified and taken into solution.
- b. Safety for control module circuit: For the circuit safety purpose, it could be fitted into an electronic circuit enclosure and the wire harness can be tied neatly.

### **5.2.2 Project Improvement Suggestion**

Many problems have been encountered to make this project become successful and the problems have been stated in the previous chapter. Thus some suggestions for a future project title about this control module are as follows:

- a. The project should be divided into clear several areas for each student
- b. Specific work scope should be focused
- c. The main objective of “Final Year Project” should be revised and stated clearly
- d. Suitable amount of time should be provided.

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## APPENDIX A

### GANTT CHART

[illegible]



## APPENDIX B

### BILL OF MATERIALS

**Bill Of Materials For Hybrid Simulation.DSN**

**Design Title** : Hybrid Simulation.DSN  
**Author** : <NONE>  
**Revision** : <NONE>  
**Design Created** : Thursday, May 23, 2013  
**Design Last Modified** : Monday, May 27, 2013  
**Total Parts In Design** : 48

**11 Resistors**

<u>Quantity:</u>	<u>References</u>	<u>Value</u>	<u>Order Code</u>
4	R1, R6, R8, R10	330R	M330R
4	R2-R5	10k	M1k
3	R7, R9, R11	1k	M1k

**7 Capacitors**

<u>Quantity:</u>	<u>References</u>	<u>Value</u>	<u>Order Code</u>
3	C1, C2, C7	0.1uf	
1	C3	1000uf	
1	C4	100uf	
2	C5, C6	22pF	

**2 Integrated Circuits**

<u>Quantity:</u>	<u>References</u>	<u>Value</u>	<u>Order Code</u>
1	U1	PIC16F873A	
1	U3	7805	

**3 Transistors**

<u>Quantity:</u>	<u>References</u>	<u>Value</u>	<u>Order Code</u>
3	Q1-Q3	2N2222	

**9 Diodes**

<u>Quantity:</u>	<u>References</u>	<u>Value</u>	<u>Order Code</u>
4	D1, D3, D5, D7	LED-YELLOW	
2	D2, D8	1N4001	
3	D4, D6, D9	1N4148	

**16 Miscellaneous**

<u>Quantity:</u>	<u>References</u>	<u>Value</u>	<u>Order Code</u>
7	ESTART, MFUEL, MHYBRID, PBM-RL3		
1	ICSP	TRANS 10 DIL	
3	J1-J3	TBLOCK-I3	
1	LCD1	LM016L	
1	RV1	4.7k	

1	RV2	1K
1	SUP_PIC	TBLOCK-I2
1	X1	CRYSTAL

*Monday, June 17, 2013 7:01:31 AM*

## APPENDIX C

### FULL PROGRAMMING



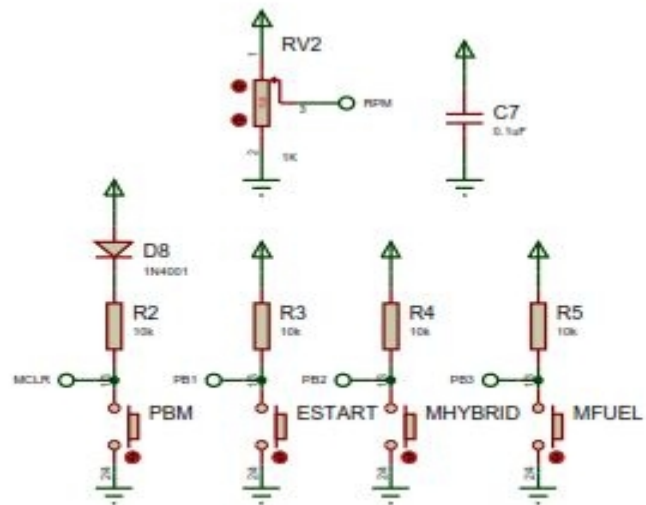
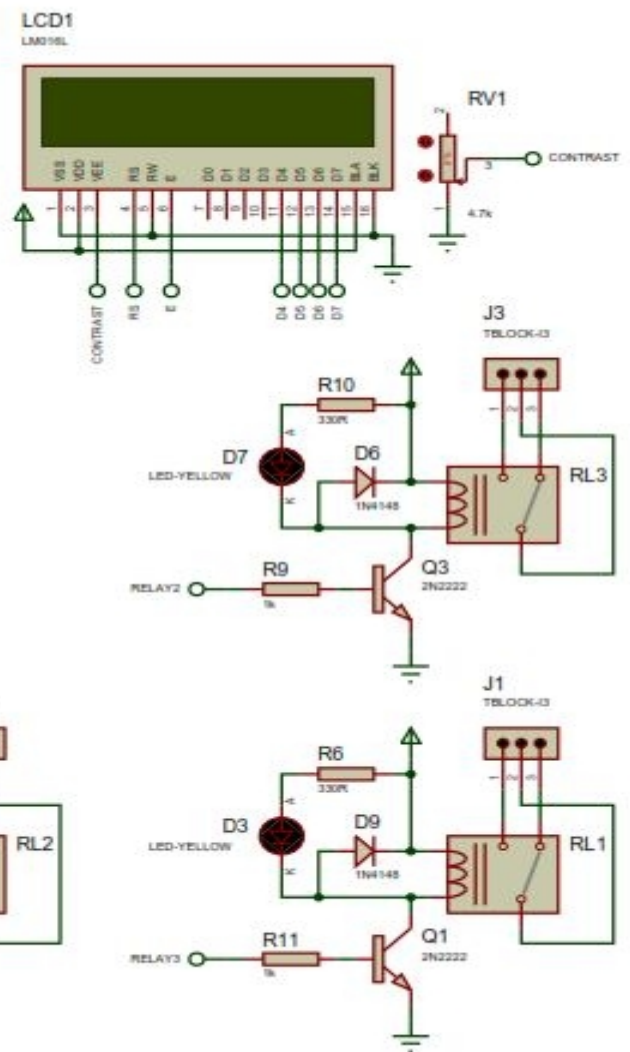
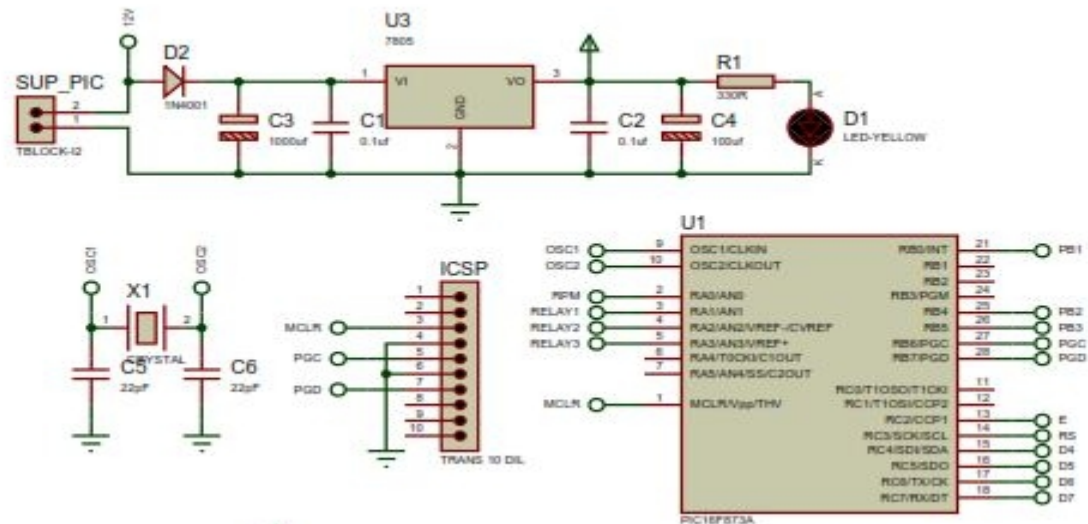




## APPENDIX D

### FULL CIRCUIT SCHEMATIC DESIGN

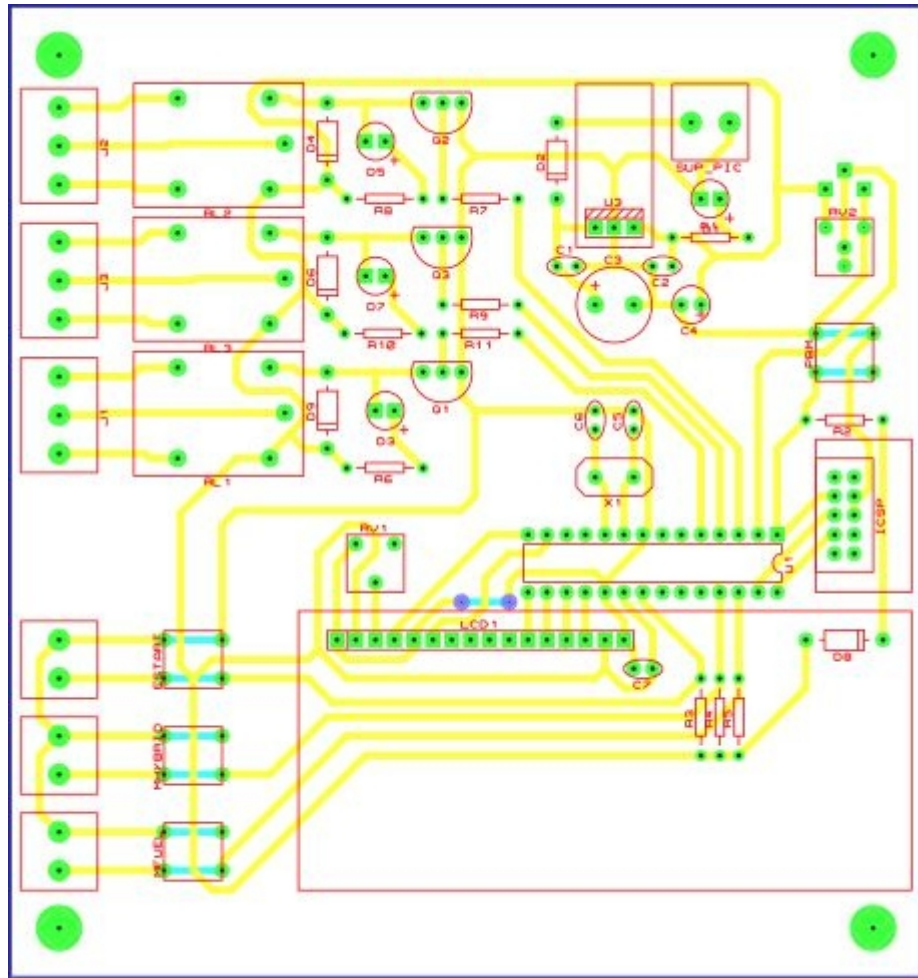




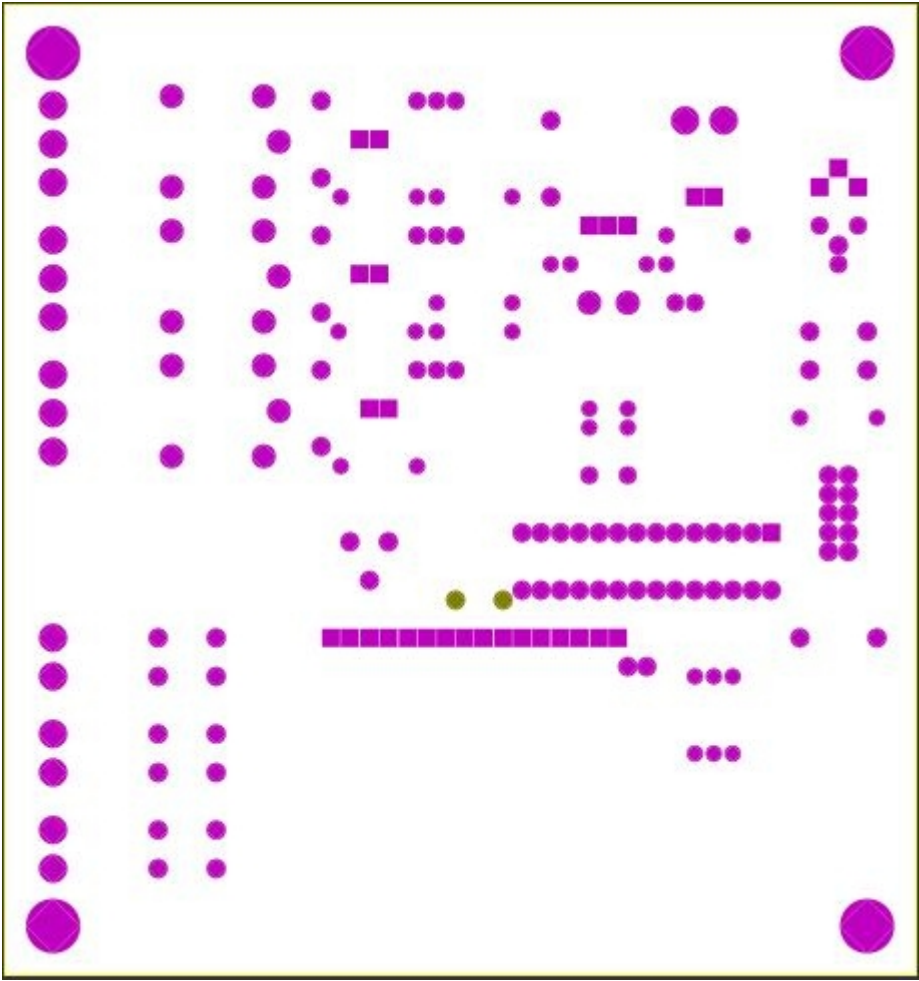
## APPENDIX E

### FULL CIRCUIT PCB LAYOUT

## ARTWORK MODE



SOLDER RESIST MODE



## DRILL PLOT MODE

