IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 2 Issue 4, April 2015.
www.ijiset.com
ISSN 2348 – 7968

Design of Synchronic Generator and Control System for Hybrid Vehicles

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Abstract
Today regarding excessive use of fossil fuels, the critical pollution conditions of environmental has occurred. It leads the authorities to the use of fuel-efficient vehicles that have less polluting than internal combustion engines. Hence, the hybrid vehicles are introduced as suitable choice that has been formed from internal combustion and electrical vehicles. The design of synchronic generator for hybrid vehicles and its control in various road conditions is purpose of this paper. Many methods have been proposed for controlling electric motors which have complex mathematical relations; however, the use of intelligent algorithms to control this type of engine has been common in recent years. In this study, in order to control of engine speed and battery consumption rate the flowchart switching method is used.
Keywords: *Switching, State flowchart, Hybrid Vehicle, Synchronic Generator*

1. Introduction

In one hand by increasing the number of vehicles and in other hand due to the less energy and environmental concerns, a considerable part of research has gone into the use of clean and renewable energy instead of fossil fuels. Fossil fuels are non-renewable and releases greenhouse gases into the atmosphere during combustion.
Nowadays the largest companies in world, including companies such as Toyota, Honda, Mitsubishi, Ford, Fiat, General Motors, DaimlerChrysler, Nissan, Peugeot, and etc show special attention to hybrid cars. The success of these products has been so impressive that from December 1997 to early 2000, more than forty thousand of Prius products for company Toyota have sold.
Hybrid vehicles take energy through the two energy source of an energy conversion unit (such as a combustion engine or fuel cell) and an energy storage device (such as batteries or ultra-capacitors). Energy conversion unit is enabling to getting power from gasoline, methanol, compressed natural gas, hydrogen or other alternative fuels it. Hybrid vehicles have the potential to have 2 to 3 times higher efficiency than conventional cars. Such systems have many advantages, among which, it is possible to mention the following:
1. Use fewer fossil fuels.
2. Reduction damage to the environment
Due to this characteristics and needs numerous studies have been conducted on hybrid cars. For example, [1] investigate a losses in a different hybrid systems is discussed. Available vehicle hardware and control modes are investigated in [2]. Optimize control strategy to fuel economy and greenhouse gas emissions has been discussed in [3]. In paper [4], a systematic process for designing a hybrid vehicle power transfer concepts have been considered.

2. Problem Statement

The power output for ac machine is as follow:

$$Q = c_0 D^2 L n \quad (1)$$

The amount of c_0, which considered as output coefficient, is Proportional to the product of the specific electrical loading and loading of special magnetic. So the result is that the size and cost of the generator motor is reduced with increasing these amounts. Thus particular loading values are increases as possible to decrease size of generator engine. But since the cost and size is not the only important factor in the design, Designer tries to increase the amount of the particular loading, generator engine performance characteristics such as temperature and rate efficiency have not the opposite effect.

$$c_0 = 1.11\, \pi^2 B_{av}\, ac\, K_w \times 10^{-3} \quad (2)$$

Power factor is said to the ratio of real power to apparent power and has value between 0 and 1. The real power shows the ability of a consumer to convert electrical energy into other energy. While the apparent power come from the difference between voltage and current. Low power factor (larger actual power than the apparent power) in a circuit, cusses increasing the current in circuit and thereby higher losses in the circuit.

The produced power by m phase machine which has a circuit in each phase is obtained from the following equation:

$$P_{in} = m\,V_{Ph} I_{Ph} \quad (3)$$

By assuming equal length of the stator and stator inner diameter D and L values are specified:

D=L=177/5 mm

There is no specific rule choosing the number of slots in the stator. However, a large number of slots require more slot insulation and more the number of coil windings, insulation and installation and this would be cost-rise building. On the other hand, flux leakage and its share in leakage reactance of the motor, is inversely proportional to the number of slots per pole per phase. Thus, the number of slots per pole per phase must not be lower than two otherwise the leakage reactance would be high.

$$q = \frac{number\ of\ stator\ slot}{number\ of\ phase \times number\ of\ pole} \leq 2 \quad (4)$$

$$number\ of\ stator\ slot S_{ss} = 2 \times 4 \times 3 = 24\ slot$$

T_s is number of winding turns per stator phase which is obtained from the following equation. To obtain amount of T_s, the values of magnetic flux of each pole, nominal frequency and voltage of each stator phase must be achieved.

$$T_s = \frac{E_s}{4.44\, f\, \emptyset\, K_w} \quad (5)$$

All the part of core is not formed of iron but some parts of it formed by air ducts and creating insulator between the sheets and air gap makes to consider a space factor for iron which is depends on the thickness and type of insulation which its amount is normally L_i=0/95 L so we will have:.

$$\emptyset = B_{av}\,\tau\, L_i \quad (6)$$

For step of pole can be written:

$$\tau = \frac{\pi D}{p} \quad (7)$$

Nominal frequency can be obtained with respect to the synchronous speed

$$f = \frac{p}{2} \times n_s \quad (8)$$

E_s is the voltage of each stator phase and its value can be assumed to 0.97 of nominal voltage.

$$E_s = 0.97 V_{Ph} \quad (9)$$

According to equation (9), for voltage of each stator phase will have:

$$E_s = 0.97 \times 220\ V = 213.4\ V$$

According to equation (8), for Nominal frequency will have:

$$f = \frac{4}{2} \times 16.6667\ Hz = 33.3334\ Hz$$

According to equation (7) and (6), for the magnetic flux poles $\emptyset$ will have:

$$\emptyset = 1T \times \frac{\pi \times 0.1775m}{4} \times\ 0.95 \times 0.1775m \Longrightarrow$$
$$\emptyset = 23.5077 \times 10^{-3}\ wb$$

According to equation (5), for T_s winding number will have:

$$T_s = \frac{E_s}{4.44\, f\, \emptyset\, K_w} \Longrightarrow$$
$$T_s = \frac{213.4\,V}{4.44 \times 33.3334\ Hz \times 23.5077 \times 10^{-3}\ wb \times 0.955} = 64.2271 \simeq 64$$

If m is the number of phases, the total number of conductors in stator for three-phase motors is equal to $6T_s$.

Total number of conductors in the stator = m × 2 × T_s

Total number of conductors in the stator = 6 T_s

Total number of conductors in the stator = 6 × 64 = 384

Due to that the stator has 24 slots, the number of conductors per slot that shows by Z_{ss} is obtained as follow.

$$Z_{ss} = \frac{Total\ number\ of\ conductors\ in\ the\ stator}{slot} \quad (10)$$

$$Z_{ss} = \frac{384}{24} = 16$$

In the design process of armature winding, If the number of conductors per slot be odd or fractional number, we choices the next larger integer or next even number respectively for winding single-layer or double-layer winding coils step.

Mechanical step angle for a complete cycle of each stator slot is obtained, so that perimeter of stator which is equivalent to 360 is split on total slots.

$$\gamma_{mechanical} = \frac{2\pi}{total\ slot} \quad (11)$$

$$\gamma_{mechanical} = \frac{360^\circ}{24} = 15^\circ$$

Use of four poles makes that the slots of stator forms the two pairs magnetic poles S and N. Thus, the set of slots are placed under pole S and another set are placed under poles N.

$$\gamma = \frac{p}{2}\,\gamma_{mechanical} \quad (12)$$

$$\gamma = \frac{4}{2} \times \frac{360^\circ}{24} = 30^\circ$$

The following table shows how each arm of coil for a phase in poles enters. Entry the arm coil from pole N and exit other arm coil from S pole.

Following equation is used to calculate the coefficient step:

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$$K_p = \sin\frac{\text{coil step}}{2} \qquad (13)$$

$$K_p = \sin\frac{150^{\circ}}{2} = 0.9659$$

The proportion of sum vector of motive force to its algebraic sum is called distribution coefficient.

$$K_d = \frac{\sin\frac{q\,\gamma}{2}}{q\,\sin\frac{\gamma}{2}} \qquad (14)$$

$$K_d = \frac{\sin\frac{2\times 30^{\circ}}{2}}{2\,\sin\frac{30^{\circ}}{2}} = 0.9659$$

Winding coefficient is achieved from the following equation:

$$K_w = K_d \times K_p \qquad (15)$$

$$K_w = 0.9659 \times 0.9659 \Rightarrow K_w = 0.933$$

Table 1. Entering and exiting coil arms at the poles

U_1	U_2	V_1	V_2	W_1	W_2	Phase / pole
1	2	5	6	9	10	N
7	8	11	12	15	16	S
13	14	17	18	21	22	N
19	20	23	24	3	4	S

Core losses vary directly with flux density tooth. Thus, high flux density is not desirable in the teeth and since the density of teeth should not exceed from 1.7 Tesla, The minimum width of the stator teeth is obtained from the following equation.

$$w_{t\,min} = \frac{\frac{p\,\emptyset}{S_{ss}}}{1.7\ L_i} \qquad (16)$$

$$w_{t\,min} = \frac{\frac{4\times 24.1473\ \times 10^{-3}\ wb}{\text{۲۴}}}{1.7\times\ 0.95\times 0.1775m} = \text{۱۴/۰۳۹۳}\ mm$$

Average flux density in the stator core should not exceed 5.1 Tesla. So that half of the pole flux passing through core and the minimum depth of the core which is called the yoke thickness is obtained.

$$d_{cs} = \frac{\frac{\emptyset}{2}}{1.5\,L_i} \qquad (17)$$

$$d_{cs} = \frac{\frac{24.1473\ \times 10^{-3}\ wb}{2}}{1.5\times\ 0.95\times 0.1775m} \Rightarrow d_{cs} = 47.7337\ mm$$

Stator slot step is obtained by dividing the air gap to the stator slots.

$$y_{ss} = \frac{\text{Surface of air gap}}{\text{Total stator slots}} \qquad (18)$$

$$y_{ss} = \frac{\pi\ D}{S_{ss}} = \frac{\pi\times 0.1775m}{24} \Rightarrow y_{ss} = 23.2346\ mm$$

$$\text{Slot width} = \text{slot step} - \text{Tooth width} \qquad (19)$$

By using above equation, the Slot width is achieved.

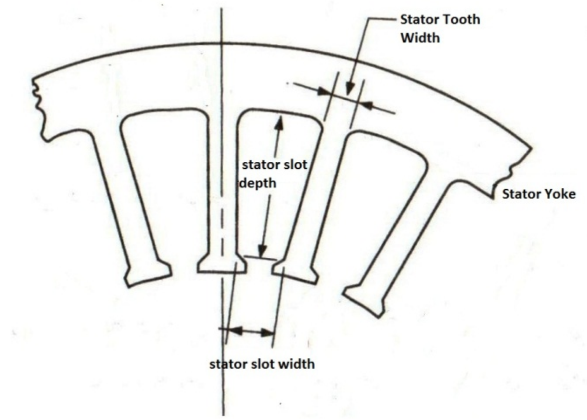

Figure 1. Design of stator components

Due to limitations in the design of the yoke thickness, its thickness can be assumed equal to 40 mm. This assumption helps to increase and improve current density and also can save used material.

$$D_o = 177.5\ mm + 2\times 18.3906\ mm + 2\times 40\ mm = 294.2812\ mm$$

When the numbers of conductors per slot and conductor cross sections are determined, with consider a value for the slot occupancy coefficient, the approximate area of slot can be achieved.

$$A_{ss}\times SSF = Z_{ss}\times a_s \qquad (20)$$

In this relationship, SSF is the coefficient of the stator winding refilled and typically its amount is considered equal to 0/5.

$$a_s = \frac{A_{ss}\times SSF}{Z_{ss}} \Rightarrow a_s = \frac{169.107\ mm^{\text{۲}}\times 0.5}{16} = 5.2845\ mm^{\text{۲}}$$

$$\delta_s = \frac{I_{zs}}{a_s} \Rightarrow \delta_s = \frac{11.8371A}{5.2845\ mm^{\text{۲}}} \Rightarrow \delta_s = 2.24\ \frac{A}{mm^{\text{۲}}}$$

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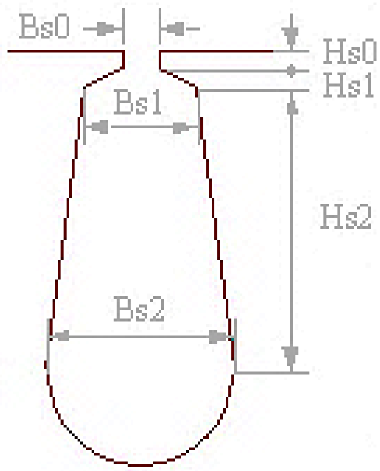

Figure 2. Different locations in slot

Table 2. The size of the stator slot

slot Dimensions (mm)	Size
1	H_{s0}
2	H_{s1}
14	H_{s2}
2/8	B_{s0}
8/5	B_{s1}
11/6	B_{s2}

In the following figure one pole of the machine is shown. Simulation for a pole of machine is considered to be symmetric, this is to reduce the large amount of computing time and increasing the accuracy of the results was performed.

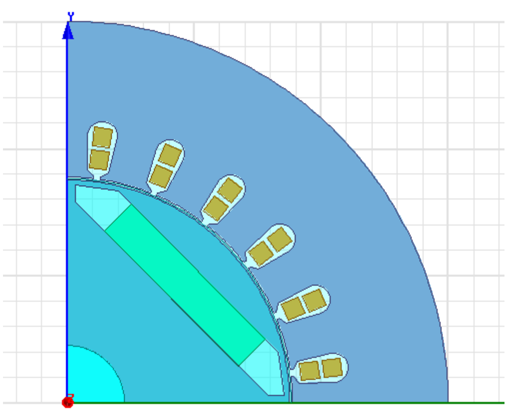

Figure 3. One pole of machine

Grid and grid density in different parts of the machine shows below figure. As shown in this figure, to accurately calculate the number of grid used in the gap is much larger than the other part.

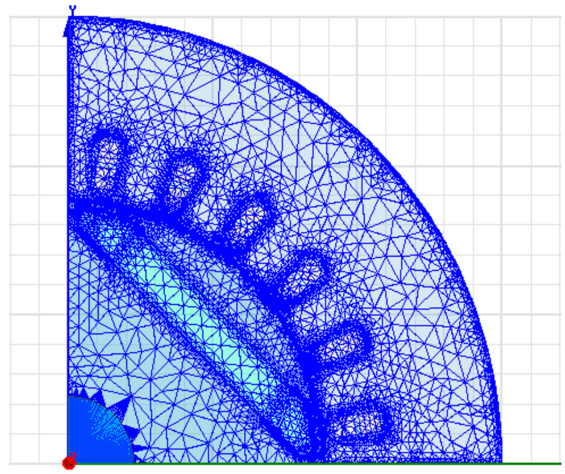

Figure 4. Grid

Magnetic flux lines are shown in Figure 5, as it can be seen the flux passing through the magnet from the rotor side to the stator side, which has been given as command to software through global axis and with respect to the poles of the magnet, magnetic flux changes which is sine, is from negative to positive.

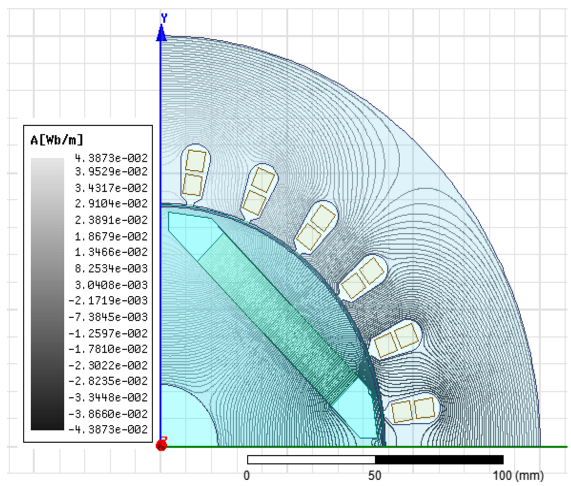

Figure 5. The lines of magnetic flux in machine at no-load mode

Figure 6 shows the magnetic flux variations curve in terms of distance a pole. As shown in this Fig, the Amplitude of magnetic flux at the beginning started from -0.04 Weber per Meter and at the end of the first quarter of the first pole is achieve to amount 0.04 Weber per Meter. However, due to the sine of the value, this value is effective and accordance to equations and calculations, its maximum amount is obtained.

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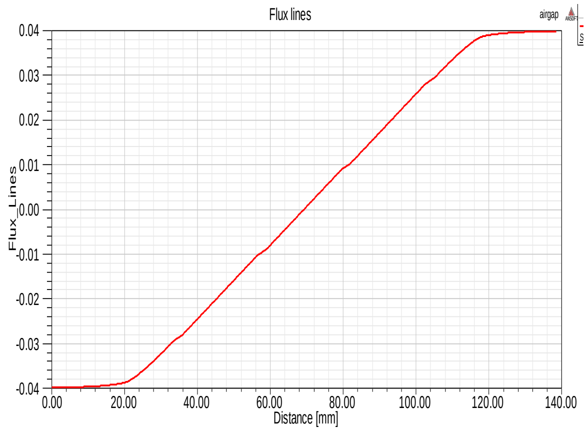

Figure 6. Curve of the magnetic flux in the no-load mode

The following figure shows the flux density variations in a quarter of machine. As it can be seen, this value has largest state in the edge of the poles of the magnet and from this point goes into saturation.

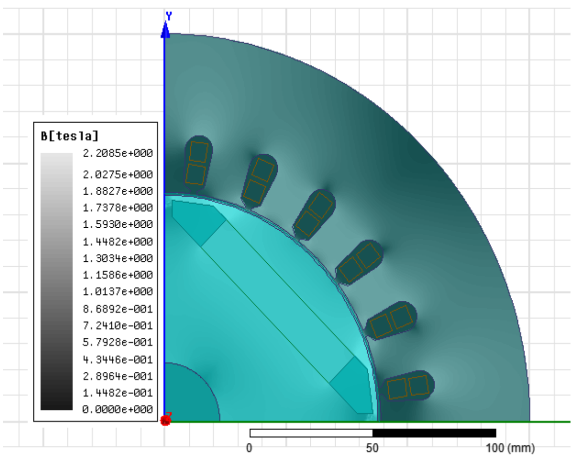

Figure 7. The size of flux density in different parts of the machine in no-load mode

Following figure shows the flux density curve in the air gap, regardless of the current in the stator winding, this flux density is calculated based on B_r=1/2 T and for magnet is obtained.

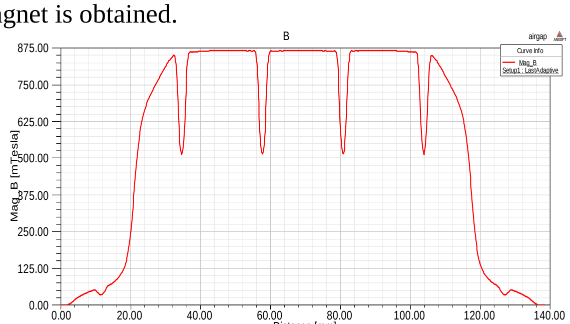

Figure 8. The radial component of the air gap flux density curve

The passage of the magnetic flux density vector as well their size in among of stator conductors at no-load mode has been shown.

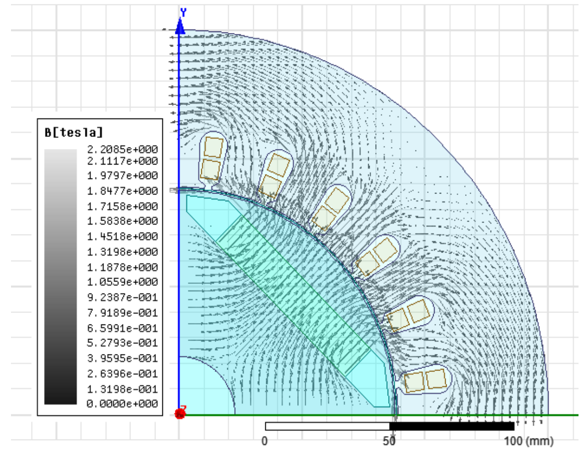

Figure 9. Magnetic flux density vector machine at no-load

Amount of voltage for each stator phase at no load is shown in the following diagram. This Figure is almost sinusoidal and appears alternatively. Whatever this figure is closer to sinusoidal is better, because this distortion in the waveform caused by existence of harmful harmonic at machine operation. To illustrate the performance of machine in a steady state sinusoidal current is injected into each phase.

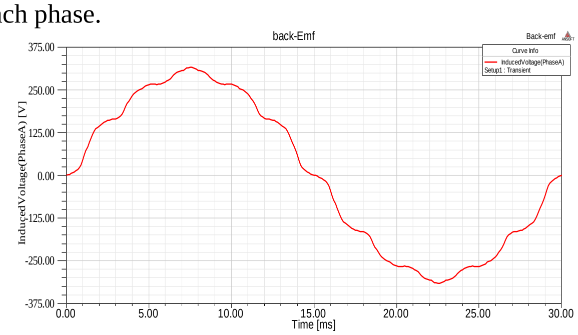

Figure 10. Voltage of each phase stator

Tooth torque, is additional torque that can be achieved by interaction between the stator teeth with a magnet. This moment is desired up to 1/5 of the total machine torque. In this machine dent is in maximum torque equal to 2.5 Nm.

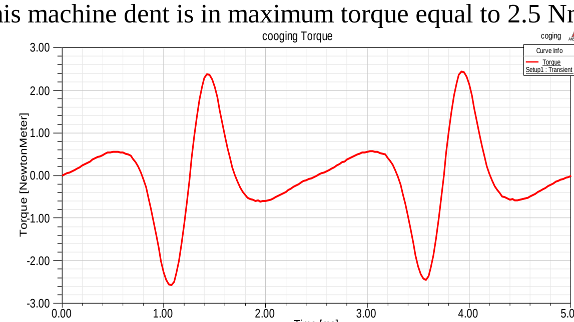

Figure 11. Tooth torque

The output torque is as follow:

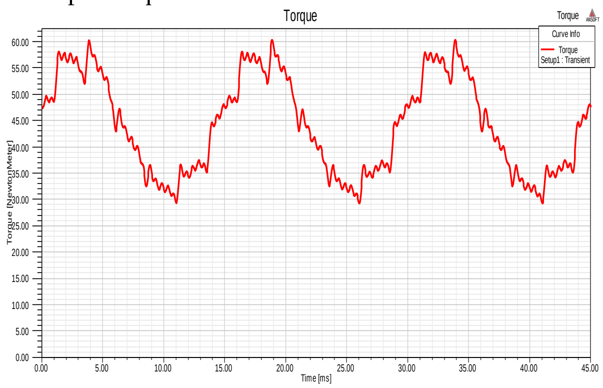

Figure 12. Total machine torque

At first, Depending on the arrangement of the internal combustion engine and electric motor, that indicated in figure 13, for this vehicle two switches is designed in two parts and these two switches are associated together by a controller.

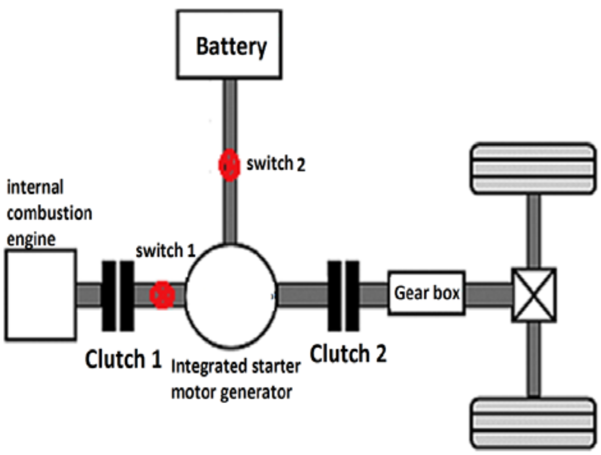

Figure 13. The propulsion systems arrangement of the internal combustion engine and electric motor vehicle

First switch task is to switch on and off the clutch (1), and the second switch task is to battery connection and the motor conversion into a generator and vice versa. This switching method is based on measuring engine speed and measure the battery capacity is performed. In many of measurements the path are considered sectional, But in this simulation, considered path for vehicle has different speed. Movement in the determined path with the determined speed are input of controller has been proposed as a condition of vehicle dynamics. The desired path given for this vehicle and the speed of the vehicle in this path are shown in Figures 2 and 3 respectively.

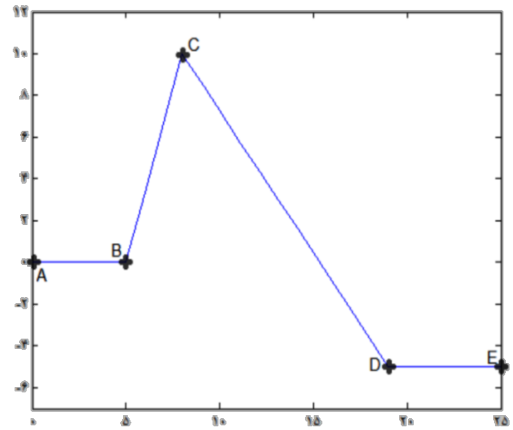

Figure 14. Path of the vehicle

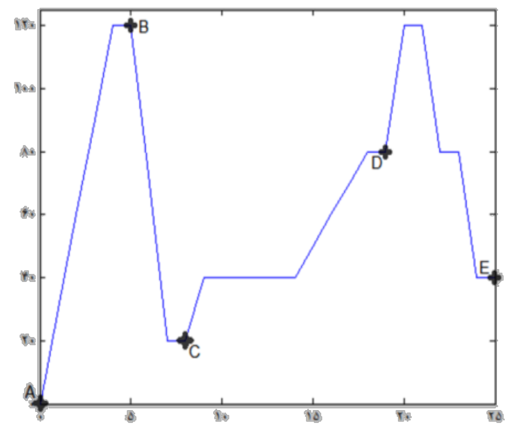

Figure 15. Speed of the vehicle

The desired path consists of several parts with different characteristics to all the switching states occur in this path. Compliant switching is happens under two conditions, these conditions are as follow:

A) If the battery capacity reaches to 100%. In this case, according to the other conditions electric motor is used.

B) If the vehicle is moving with a speed less than 1300 rpm. In this case, the electric motor is used.

According to the above opposite switching happens under two conditions that these conditions are:

A) If the battery capacity reaches 20% of the battery capacity. The internal combustion engine must be used.

B) If the vehicle is moving with speed more than 1300 rpm. In this case, the internal combustion engine is used.

In fact, assuming switching as follows that if the battery capacity reaches 20% of the total capacity of the battery, the switch number 2 is operates and electric motor converted to generator, also switch number 1 operated so that clutch number 1connects and gasoline engine will be in thrust circuit and as long as the battery does not reach 100% capacity, conversely operation, means compliant

IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 2 Issue 4, April 2015.
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ISSN 2348 – 7968

switching (switch number 2 convert generator to the electric motor and switch number 1 cut clutch number1 so that gasoline engine, removes from thrust circuit) will not occur. Noted that in this case until speed does not reach to1300 rpm or above, according to speed diagram of generator motor, the generator mode has not happened, Generator is not able to charge the battery. Also by considering second assumption of switching if the vehicle wants to move with speed of 1300 rpm, at this time, the vehicle speed with electric motor is 60 kilometers per hour. According to the diagram of the motor generators, generator mode will occurs at higher speed of 1300 rpm, In this case, the electric motor is not able to drive and the electric motor must become a generator. So at speed of 1300 rpm switch number 2 operated and electric motor converts to generator, switch number 1 operated so that clutch number 1connects and gasoline engine will be in thrust circuit and according to the speed above 1300 rpm generator is able to charge the battery. In this case, if the engine speed reached below 1300 rpm, by considering initial condition until the battery is not reached to 100% capacity, conversely operation or compliant switching will not occur.

3. Control by State Flowchart Method

In this method the flowchart diagram is used for to define the system states. In each flowchart set of rules and conditions that are associated with each state of the system is defined. To connection each flowchart with next Flowchart, we can use the set of rules those defined for system. This control method is one of the easiest and most accurate method of control which is in simplicity is able to control complex systems and applied appropriate outputs as inputs to the control system. In this method it is possible to draw desired diagram and flowchart and defined the rules relating to each of them, put state of plant into the desired position and generates an input control signal and applied to relevant plant [7-5]. In the following the description of the control that used in this study is presented. Figure 16 shows a schematic of control between components and heart of control systems.

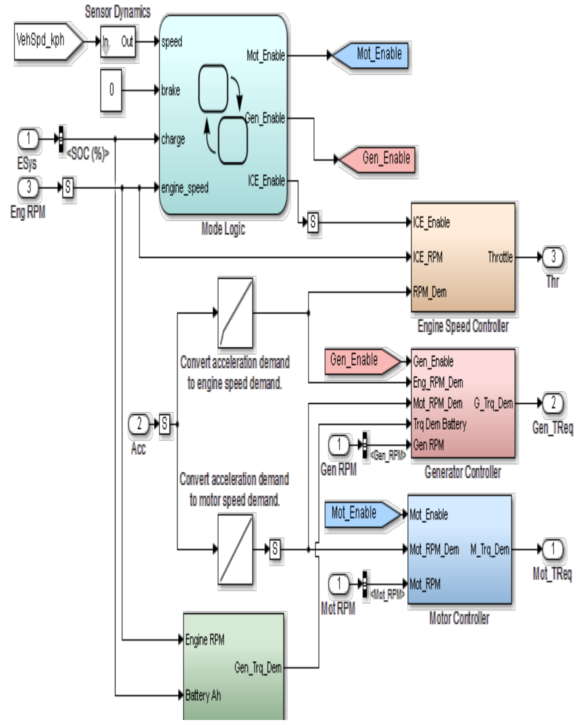

Figure 16. Schematic view of control between components and control heart

Control block components are:
The mode Logic block diagram that in fact the heart of control system is located in it and its duty is to generate the control signal for electric motors and generators, as well as the internal combustion engine. As can see in the above figure, the inputs are:

- Dynamics of speed related to vehicle is on the move.
- Condition of brake.
- Variable battery charge.
- Variable related to speed motors of vehicle.

Also output includes:

- Enable signal of electric motor
- Enable signal of electric generator
- Activation signal related to internal combustion engine

Flowchart of the control system in mode logic is shown in Figure 17.

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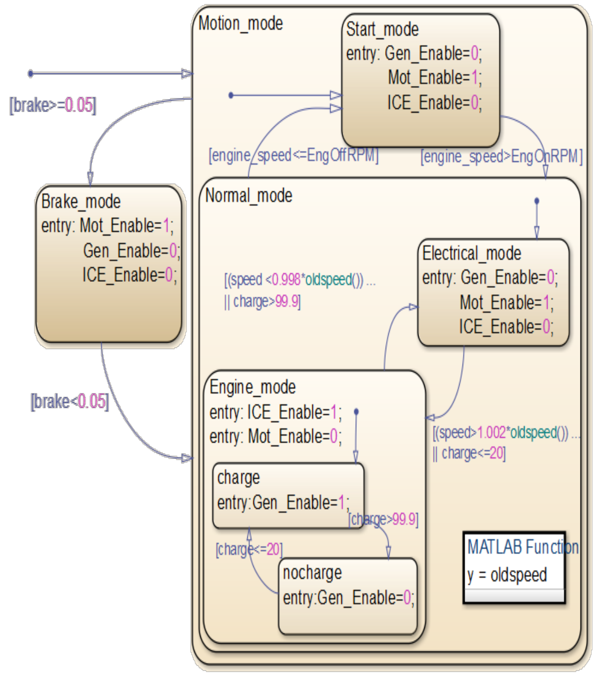

Figure 17. Flowchart of control system

In this system the assumptions described in the previous section have been considered as follow. In the mode logic block diagram that known as the heart of the control system, the motion mode of vehicle is placed which is the main mode of system and the other modes are a subset of this mode.

One of the assumed modes is starting mode. The output of starting mode is as follow.

Activation signal of electrical generator = 0

Activation signal of electric motor = 1

Activation signal related to internal combustion engine = 0

Other mode is normal mode.

The condition to entry this mode is the internal combustion engine is turned on and the condition to exit of this mode is the internal combustion engine being turned off. The outputs of this mode are as follow.

At the normally mode there are two subset which are known as electrical mode and engine mode. The condition for Conversion thee mode to other is as follow.

If the moment speed is less than 0.998 previous moment speed or battery capacity is greater than 99.9 percent, then the mode is transferred from electrical to gasoline.

If the moment speed is more than 1.002 previous moment speed or battery capacity is less than or equal to 20 percent, then the mode is transferred from electrical to gasoline.

The outputs of electrical mode are as follow:

Activation signal of electrical generator = 0

Activation signal of electric motor = 1

Activation signal related to internal combustion engine = 0

Gasoline motion mode outputs are as follow.

Activation signal of electric motor = 0

Activation signal related to internal combustion engine = 1

It should be noted that the battery charge is assessed in gasoline motion mode and if the battery charge is greater than 99.9 percent the generator mode is turned off and if battery charge is less than 20 percent the mode generator is turned on.

4. Simulation Results

The simulation results are presented in this section. Figure 18 shows the switching diagram.

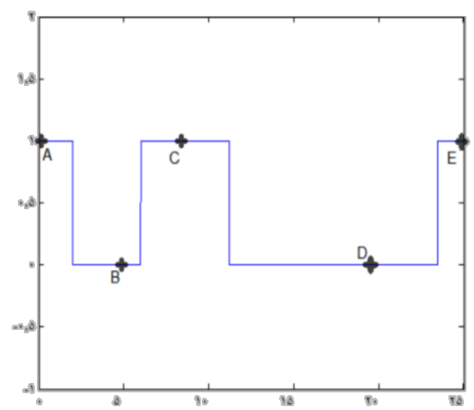

Figure 18. Switching diagram

As it clear from figure 18, the switching has to state (on and off). These two states are simile to 0 and 1 in controller. Reach from 0 to 1 state is the compliant switching state; shows the converts from generator to electric motor and the change state from 1 to 0 is the opposite switching state which shows the converts from electric motor to generator. By starting this mode, vehicle with internal combustion engine is started. At 2 minute vehicle motion is change from electrical mode to internal combustion engine that shoe the first switching in the path. This switching has occurred to increase the output speed engine, as can be seen in Figure 21. At 6 minutes compliant switching state is occurred and again motion takes place by the electrical motor. This switching is done in order to change speed as seen in Figure 20. At 11 minute again the opposite switching is done. This switching is done because the battery capacity is reached to 20% of the total capacity of the battery; this is shown in Figure 19. And then the last compliant switching is done at 23.5 minute and its reason is to reduce the speed and reach to the moving speed of electrical motor. Figure 19 shows a diagram related to change in battery charge.

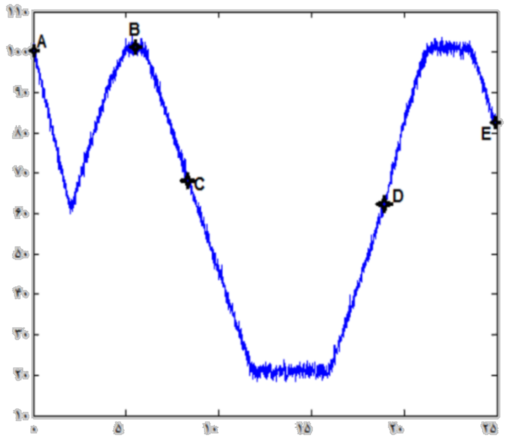

Figure 19. Change in battery charge

In Figure 19, the diagram of the battery capacity can be seen, at point A that is the beginning of the vehicle path, and the capacity is 100%. With respect to the path and speed of movement, vehicle will start with electric motion. At 5 minutes battery charge is reached to its maximum but considering to the fact that speed of output engine is at the generator, switching has not been done. At 6 minute, the motor speed is reduced and placed in the range of generator and at this time switching will be performed. Also at 11.5 minute because the capacity is reached to 20% switching is done but because the speed is down and motor generator at generator state is not capable to operating, battery charging is starts at 16 minutes. This charging continues until 21.5 but with filling battery capacity due to being outside the range of engine, switching is not performed.

The below figure shows the output speed at engine mode. That exactly at times the switching is performed, motor is exited the motion path or entered the motion path.

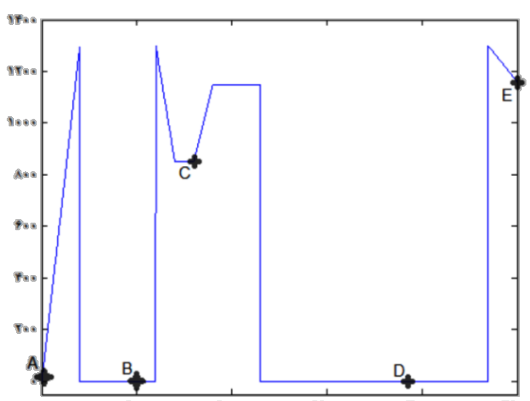

Figure 20. output speed diagram at the engine mode

The below figure shows the output speed at generator mode.

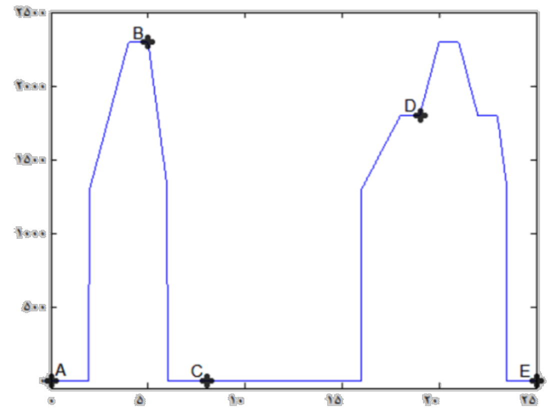

Figure 21. output speed diagram at the generator mode

As is clear from the figures, by considering assumptions of switching, this operation has been performed correctly by the proposed method.

4. Conclusions

Nowadays due to increased environmental pollution produced by internal combustion engines, hybrid vehicles as an option to instead of internal combustion engine are considered. Therefore, many studies have been done on it.in this paper switching of motion system and Hybrid vehicle control by using flowchart control in various road modes was studied. As shown the proposed method performed the switching ideally.

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