Hybrid Electric Vehicle: Designing a Control of Solar/ Wind/ Battery/ Capacitor/ Fuel Cell Hybrid System

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Abstract— This paper presents the design, simulation and control of a Hybrid Electric Vehicle (HEV) based on renewable energy sources. The proposed HEV design utilizes solar energy, wind energy, Fuel Cell (FC) which generates energy from Proton Exchange Membrane (PEM) and a Super Capacitor (SC) to meet the strong torque requirements. The vehicle incorporates a battery pack in conjunction with a SC for the power demands and FC as the backup energy supply. An alternator connected to turbine blades will rotate using wind energy when the car is moving forward and will produce electricity to charge the battery. The aerodynamics force and all the respective resistive forces due to the wind turbine have been considered in the simulation. The design aims to ensure zero carbon emission, energy efficiency and light weight that will incorporate the use of in-wheel motors to eliminate the mechanical transmissions. To meet the vehicles power demands, the selection of energy sources are controlled by a rule based supervisory controller which follows a logical sequences that prioritize energy sources with the SC as a source in vehicle stop-and-go situations while battery will act as the primary source, FC as a backup supply and wind and solar power to recharge the battery. The controller also controls the energy flow from the alternator and monitors regenerative braking while switching to solar charging when the vehicle is parked.

Keywords— Hybrid Electric Vehicle (HEV); Fuel Cell (FC); Super Capacitor (SC), Proton Exchange Membrane (PEM); Rule Based Control; Power Grid for HEV; Renewable Energy.

I. INTRODUCTION

For the clean and sustainable energy future, few most important issues need to be addressed which includes use of fuel for transportation, utilization of renewable energy sources and finding smart ways of energy consumption [1-2]. Energy researchers have identified that burning fossil fuels for our traditional means of transportation is one of the major cause of global warming and climate change [3-4]. As to reduce carbon footprints and become more environmentally friendly, traditional transportation systems require attention [5-6]; electric vehicles have entered the energy market as potential alternatives but these vehicles are dependent on the power grid for their battery to be charged [7].

Furthermore, few of the electric power grids are still using fossil fuels to generate electricity as a result the so called green car or Electric Vehicle (EV) are also a reason for environment pollution [8-10]. As the traditional automobile system cannot be instantly replaced by any other system, the most auspicious transportation solution is to design a new vehicle which will run completely from renewable energy sources with zero fossil fuel and/or low carbon emission which could be negligible and can be called zero carbon emission and introduce the vehicle as a part of the present transportation system.

Electric Vehicles have had recent breakthroughs in the transportation industry, shifting from fossil fuel energy to renewable [10]. A number of researchers and manufactures around the world are working towards developing “Clean-Car” [11] or “Green-Car” [12] technologies, and some of the renewable energy source options that have been explored through various studies and developments are wind and solar [13-14].

EVs rely on electric power, hence the fuel economy of such vehicles are measured in kWh per 100 miles, as opposed to miles per gallon of gasoline equivalent (mpge). The fuel economy of electric cars is dependent on the type of load carried for instance, according to [15-18] light duty electric vehicles today can surpass 100 mpge and can consume only 25-40 kWh driving 100 miles. While developing new transportation technologies, researchers or manufacturers must address carbon emissions issues together with fuel economy and efficiency of vehicles hence, clean energy sources should be selected that has low to approximately zero emissions.

In this paper, the design of a Zero Fuel Zero Emission (ZFZE) car is presented that combines solar and wind energy to charge the battery which is also the primary source, SC for regenerative braking and FC to drive in-wheel motors which is technologically new in terms of designing a sustainable energy utilization system. These energy sources and relevant technologies for such a vehicle are found in various literatures [7-11].

Solar cells connected in series or parallel are used to convert the energy from the solar to electrical energy for use in an HEV. Each solar cell will generate from 0.5V to 0.8V and these cells will be combined using series and parallel connections to form solar cell arrays. The sizing of this array depends on the load requirement of the vehicle. Advantages of a solar powered car include harvesting energy from a free and clean source, require low maintenance and produce no harmful emission. However, a solar powered car may lack speed and power of a regular car and the availability is totally dependent on the sun hours.

The fuel cell is an electrochemical device that utilizes hydrogen as its fuel and produces electrons, protons, heat and water as by-product. With continuous and constant supply of hydrogen gas to the cell, the fuel cell has the ability to produce electrical energy. The major benefit of using FC based cars is that there is no direct carbon dioxide emissions...
[19] provided if the hydrogen used in in such vehicles are renewably sourced gaseous hydrogen.

Super-capacitors have high power densities and quick charge/discharge rates and these characteristics make them useful in stop-and-go situations in the proposed design. The kinetic energy of the proposed vehicle will be captured by the SC as it brakes and this energy will be released as the car accelerates considering similar concept from [20].

Traditional vehicle’s alternator uses energy from the rotating engine but in case of proposed design, no such rotating engine is available. In this research, wind power has been used to drive the alternator for charging battery while driving. The reason of using wind power in small scale alternator is that the drag of a large wind turbine could reduce the vehicle speed. For simulation, all the resistive forces due to wind turbine have been taken into consideration.

II. STRUCTURE DESIGN OF ZFZE

The adoption of the ZFZE vehicle will significantly decrease the air and noise pollution which is particularly a major problem in urban areas. The design of ZFZE will ensure the reduction of weight of the vehicle as the mechanical transmission parts are eliminated by the use of in-wheel motors, resulting in increased autonomy. Also, the proposed design addresses the scientific challenge in the coordinated control of the renewable energy based converters supplying the wheel motors. The ZFZE from this point of view permits zero emissions at the point of utilization, therefore answers the global exigencies of sustainable development coherently with an energetic strategy for the future considering the safety, efficiency and respect of the environment. It is well known that the recent crisis on the automobile market has led many governments, to have back up policies for boosting the technologies most promising in the next future, like that of ZFZE. Even this can be interpreted as a clear address towards the development of new solutions for the urban mobility with low environmental impact.

Design of the vehicle structure has been presented in Figure 1 that shows a combination of solar and wind energy, FC and SC sources along with energy storage device (battery). It is essential to determine the type of battery that will be used for the vehicle as it consists a battery pack for energy storage. To minimize the weight of the vehicle and for the better performance, lithium ion battery could be the best choice however, after considering the cost and safety parameters, lead acid battery has been selected for this research. To meet strong torque variations, super capacitor (SC) has been used in conjunction with batteries and fuel cell (FC). The later will be supplying energy demand; the former will be used for power demand. To improve the reliability and efficiency of the proposed vehicle, SC has been added with the main drive train. The SC will be charged during the breaking and excess of energy production coming from renewable sources when needed. The SC will be used as power sources whereas the batteries and FC will be considered as energy sources i.e. SC will be employed to give immediate energy supply in the first few seconds of sudden load torque before the batteries and FC kicks in.

The entire system is shown in Figure 2, showing all energy sources, the motor load, and a controller to manage energy flow to the load. The system load consists of two DC motors directly powered either by battery or by FC. The battery is charged by a wind energy source and a solar energy source while the fuel cell can be connected to a properly installed hydrogen tank maintaining the safety. A super-capacitor is included to feed directly to the load with acceleration and charge with deceleration of the HEV. This management of energy sources is done by a controller activating switches or cutting off supply depending on information from speed sensors and vehicle activities.

III. RULE BASED CONTROL

The control operation of the vehicle is shown in Figure 3. The energy sources of the vehicle are managed by supervisory control that switches the energy sources depending on the action of the car. For instance, when the car is parked and turned off, the solar charging will be activated to charge the battery. This process is continued until the vehicle is turned on. When the vehicle is turned on, the controller reads the state of charge of the battery or FC. The battery takes priority and the fuel cell is only used if the battery state of charge (SOC) is below 30%. If both the battery and fuel cell do not have enough energy, a low energy warning is given and the vehicle remains off. If the vehicle is on and the acceleration is a value greater than or equal to 0, the capacitor is given priority to individually power the vehicles acceleration. The battery takes over if the super-capacitor lacks the SOC. The fuel cell is used if neither the battery nor the super-capacitor has enough energy. Once the vehicle is running, the controller checks if the rpm reaches 900 where-

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**Figure 1.** Schematic of multi-source system

**Figure 2.** On board electrical and control system
by the alternator has enough charging current and is allowed
to charge the battery. A plug in option also recommended
for the design in case of emergency.

![Diagram of the supervisory activation algorithm for the HEV](image)

The supervisory controller is the main manager of all energy
sources upon sensing of the actual parameters such as the
vehicle speed, SOC, wind speed, pressure and the key para-
eters of the super capacitor that are the cell capacitance,
operating voltage, equivalent series resistance, power densi-
ty, energy density, and time constant. The embedded system
of the vehicle will be mounted on the dashboard which can
either be an Arduino based system, gumstix, Xilinx or
FPGAs. Apart from these, the embedded system can also be
connected via IoT.

![Simulink result for torque, power, rpm and speed](image)

### Fig. 4 Simulink result for torque, power, rpm and speed are plotted against
time t, (sec) in horizontal axis

### IV. SIMULATION AND DISCUSSION

#### A. Vehicle Load Model

The designed model has been simulated using Simulink
and the results are presented in Figure 4 which shows the
four most important values for the wheel (Torque, Power,
RPM, and Vehicle Speed).

The inclination angle (α) is set at 10 degrees (in Simulink
model) representing the vehicle going up the hill that is
inclined relative to the horizontal.

Up to t=500 s, the vehicle accelerates. The torque is seen
to increase as the acceleration increases. The power required
by both wheels also increase with an increase in acceleration.
From time t=500 s, the vehicle starts to decelerate caus-
ing a decrease in the torque and power on the wheel. At
time t=0 s the vehicle is at rest and the power and speed
both are zero. At time t=100 s, there is an acceleration of 0.1
m/s² and so the speed increases as the power and torque on
the wheel. The acceleration is further increase from time
t=100 s to time t=400 s up to a maximum of 0.26 m/s². This
shows a corresponding increase in the power taken by the
wheel and an increasing speed up to a maximum of 56.55
km/hr. During time t=300 s and t=400 s, the vehicle is at
maximum acceleration, power, torque and speed. These are
the limits as shown in the calculations earlier.

After time t=400 s, the acceleration is decreased so as in
power and torque. However, there is no decrease in speed
since the car is still accelerating. The deceleration till time
t=700 s, due to the vehicle braking. From time t=700 s it can
be seen that the speed starts decreasing. At time t=800 s, the
negative acceleration is much more powerful and the speed
decreases at a faster rate than before.

Due to the kinetic energy of the wheel there is some form
of power generated in addition to the braking. As the car
decelerates from time t=700s, the power values become
negative meaning the wheel becomes a source to power SC.

#### B. Battery Powered Load

The load described above is then powered by a battery
bank in simulations and the results shown in Figure 5. A
72V 150Ah Lead-Acid battery bank was used for simul-
ations with a depth of discharge at 30%. The SOC of the ba-
tery is seen to decrease as it provides power to the wheel.
Since the cut off for the battery is at 30% SOC, the battery is
cut off at around time t=12780s. From the simulation re-
results, the car runs for 12780 seconds at around 56.55km/hr.
This converts to 200.75 km travelled in 3.55 hours under
just a battery source.

#### C. Fuel Cell Powered Load

The source in this section is a 72V, 6 kW FC that re-
quired hydrogen. The vehicle is subjected to the same ac-
celeration and inclination values as the battery and load simul-
a tion done in earlier sections. The objective here is to see
how long the vehicle can be driven under the same load as
the battery. This fuel cell serves to be a backup if the battery
runs out.

From the simulations (as shown in Figure 6), the fuel cell
alone is able to drive the vehicle for 3500 seconds at the
maximum speed of 56.55km/hr that converts to 0.97 hours
and a distance of approximately 55km.
Fig. 5 Simulink result for torque, power, voltage, SOC and speed are plotted against time t, (sec) in horizontal axis for battery as source.

Fig. 6 Simulink result for torque, power, SOC, current and speed are plotted against time t, (sec) in horizontal axis for FC as source.

D. Solar Panel Charging Battery

A solar panel is used to charge the 72V 150Ah Lead-Acid battery bank. The solar array is made up of 115 solar cells in series with open circuit voltage = 0.63V per cell. In this case, the system consists of the battery bank, a constant irradiance of 1000W/m², and the solar cell series configuration.

At a constant irradiance level of 1000W/m², the solar panel outputs a current of 6.4A and this is fed directly into the battery bank as shown in Figure 7. The battery is initially set to 0% state of charge representing an empty battery. With the charging current of the solar panel, the battery takes 88,000 seconds to fully charge the battery to 100% SOC, this converts to the solar panel fully charging the empty battery in 24.4 hours. Furthermore, if the vehicle with a fully charged battery can travel 200.75 km in 3.55 hours, then 3.5 days’ worth of constant charging through the solar panel can also provide enough energy for the vehicle to travel 200.75km in 3.55 hours.

E. Wind Generation Used for Charging Battery

The alternator connected with wind turbine and a DC-DC boost converter is simulated to identify the performance of wind power for HEV (charging batteries) that produces 2A charging current to charge 24 volt batteries. The system contains the alternator with DC-DC converter, a constant rpm of 1000, and the battery bank. In this research a small alternator has been used to validate the proof of concept which can be extended into large scale which requires a large size of alternator. Figure 8, shows the simulation results for the alternator charging performance which has been used both for simulation and in hardware.

Fig. 7 Simulink result for solar power charging, voltage and SOC are plotted against time t, (sec) in horizontal axis for PV array.
In Figure 8, SOC of the battery is at 0%, at time \( t=0 \) s. Since the alternator receives more than 900 RPM, it produces an output current of 2A, instantly. The vehicle is kept at a constant speed that allows the alternator blades to rotate at 1000RPM causing a constant alternator output of 2A. This charging current is fed directly to the battery for charging a 24 V (12V x2), battery pack out of 6.

The battery reached 100% SOC at time \( t=56250 \) s, converting to 15.63 hours to fully charge the couple of batteries. Based on the calculation and design, the distance covered is calculated to be 298km whereas, with other sources (i.e. FC, SC, PV), the distance covered was 200.75km. Therefore, the wind powered alternator is contributing positively and considerably to the vehicle’s energy needs by providing an extra 97.25km assuming negligible drag of the alternator blades and weight. It is worthy to note that although a small alternator is being used to simulate these results, proper installation of the turbine can help harvest energy without adding additional drag [21].

Figure 10 shows the results for proposed ZFZE system. According to the rules of the controller, the battery is the primary source and assumed to be fully charged at time \( t=0 \) s. For the first deceleration period, the empty super capacitor is charged at \( t=1000s \). The following acceleration periods are sourced by the super capacitor and not the battery in order to overcome the initial inertia. When the vehicle reached a speed of more than 20km/hr, the alternator charges the battery at a rate described earlier. When the battery reached, 30% SOC limit at time \( t=13500s \), the fuel cell takes over immediately to move the car. The fuel cell reached 0% at time \( t=17102s \) and at this time the car exhausts all its energy sources. The total distance at the control panel is obtained approximately 260km.
A wavelet energy Congress for three chemical energy availability and acceleration of the vehicle. Therefore, the controller was integrated into the vehicle which controlled the vehicle’s momentum using a SC. Through this simulation, the vehicle is seems to travel a considerable distance with the vehicle is not highly expensive and since it can gain acceleration and deceleration points along the simulation to mimic situations a vehicle may face in a typical journey. The entire system model runs using acceleration and deceleration points along the simulation to mimic situations a vehicle may face in a typical journey. The vehicle was modeled and simulated that sourced all its energy availability and acceleration of the vehicle. Therefore, the controller was integrated into the vehicle which controlled the vehicle’s momentum using a SC. Through this simulation, the vehicle is seen here to be successful.

Fig. 10 Simulink result for ZFZE: acceleration, speed, battery SOC, FC SOC, SC FOC and distance are plotted against time t, (sec) in horizontal axis

V. CONCLUSION

The proposed Zero-Fuel-Zero-Emission (ZFZE) electric vehicle was modeled and simulated that sourced all its energy needs from renewable energy sources. The vehicle used solar, wind, and a fuel cell as main energy sources while a super-capacitor conserved a major portion of the car’s energy when braking which would otherwise be lost to the surrounding. The entire system model runs using acceleration and deceleration points along the simulation to mimic situations a vehicle may face in a typical journey. Through this simulation, the vehicle is seems to travel a distance of 260km in 4.7 hours using the full PV charged battery, FC, wind powered alternator and conserving the vehicle’s momentum using a SC. A rule based supervisory controller was integrated into the vehicle which controlled the sources and prioritized the energy sources depending on energy availability and acceleration of the vehicle. Therefore, since the vehicle is not highly expensive and since it can gain considerable distance with full charged sources, the Zero Fuel-Zero-Emission Electric Vehicle concept is seen here to be successful.