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An Alternative Method to Improve Efficiency of Plug in Hybrid Electric Vehicles

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***Abstract*—The aim of this paper is to suggest a method to increase efficiency of current range extension technology by harnessing energy from exhaust gases. Plug in Hybrid Electric Vehicles (PHEVs) use an engine and a generator to power the wheel motors directly once the battery reaches a low state of charge, the surplus is used to recharge the battery. A more efficient method is needed for conservation of fuel and range extension with lower engine power. The proposed system exploits the exhaust gas energy via a turbine coupled with a switched reluctance generator in addition to the generator coupled with the engine to charge the battery directly along with the engine. This results in a more efficient system, running without idling and at a constant speed.**

***Index Terms*—hybrid electric vehicle, series hybrid, parallel hybrid, turbocharger, exhaust gas energy recovery, switched reluctance generator**

I. INTRODUCTION

Electric vehicles use power from a set of on-board batteries for propulsion. Hybrid electric vehicles (HEVs) are a class of vehicles which use both batteries and an internal combustion engines (ICEs). Range extension of a hybrid electric vehicle is the use of an internal combustion engine and a generator in conjunction with the pack of rechargeable batteries to power the motors at the wheels. The vehicle runs on the pack of batteries till the charge in the batteries reaches a low state. At this time, the ICE coupled to the generator is introduced into the active powertrain and supplies power to the wheel motors. Surplus charge from the engine is used to recharge the battery. HEVs combine the advantages of an ICE powered vehicle and an electric vehicle (EV).

II. OVERVIEW OF CURRENT SYSTEMS

Plug in Hybrid Electric Vehicles (PHEVS) are a type of HEVs which use high charge density batteries that can be conveniently charged using a conventional wall socket. The primary advantage of a plug in hybrid electric vehicle is that its fuel is versatile. It can run on electricity obtained conveniently from the power grid or gasoline. PHEVs are cleaner than conventional ICE powered cars as they run majorly on electric power. Hence, emissions are lower and overall fuel efficiency of the vehicle is higher. PHEVs appear in two broad architectures, namely the series drive and the parallel drive. Figure 1 shows simple schematics of the same [1-5, 13, 14].

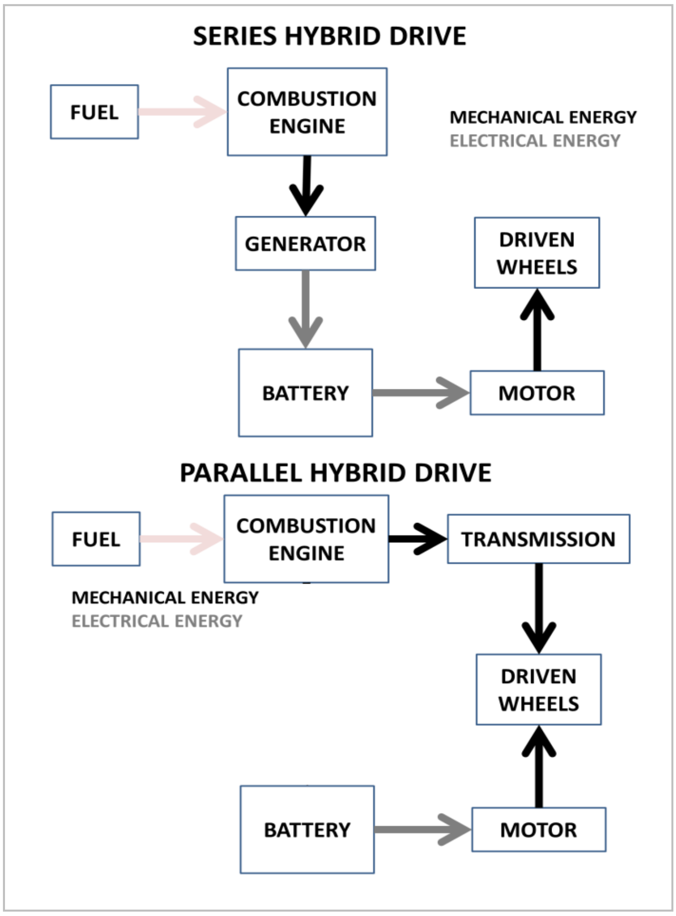

Figure 1 Series and parallel hybrid powertrain

In the series hybrid drive, the vehicle is basically electric with an on-board battery charger. This battery charger is usually an ICE coupled with a generator which drives the wheel motors and excess charge is supplied to the batteries. An alternate system where only the batteries are charged is also prevalent. When the battery reaches a predetermined low state of charge (SOC), the ICE coupled to the generator is turned on which then either recharges the battery or supplies power directly to the wheel motors. The ICE is turned off when the battery reaches an acceptable SOC. In the series drive, significant amount of energy is supplied from regenerative braking and down slope driving. It should be noted that there is no mechanical connection between the engine and the wheels [1-3, 5, 13, 14].

The series drive offers several advantages conducive to city driving. The engine is designed to operate at peak efficiency with an optimum combination of speed and torque. Also, the engine maintains this efficiency at stop starts, which usually lead to losses in efficiency in a non-hybrid ICE powered vehicle. However, in a series drive, the primary drawback is that there are two energy conversions from the ICE to the wheels, namely from the ICE to generator and from the generator to the motor. If the power from the ICE is routed to the batteries, further energy conversions occur. These conversions lead to losses.

The parallel hybrid drive consists of an ICE and motors. In this system, the ICE and the wheel motors are capable of working independently or in synchronization to propel the vehicle. This ensures that the vehicle receives sufficient amount of torque at any driving situation. The most commonly used strategy is to use the motor only at low speeds and use the ICE at high speeds. In other words, the motor is used for city driving conditions as it is more efficient than the ICE, while the ICE is used for highway driving as it is capable of generating high power. At this time, the wheel motors can be used to recharge the battery onboard the vehicle.

The parallel hybrid drive offers desired torque at any given point of time at the systems highest possible efficiency. Also, this architecture makes use of existing technology with respect to the engine, generator and the motors. However, the parallel architecture needs a complex control system as there are multiple configurations possible for the system [1-3, 5, 13, 14].

The commonly used configuration in production HEVs is the series-parallel hybrid drive which combines the advantages of series and parallel systems. The ICE is capable of independently propelling the vehicle or charging the batteries when the electric motors are in use [12].

III. PROPOSED SYSTEM WITH WORKING PRINCIPLE

The proposed system is a variation of the series hybrid system but with the use of exhaust gas recovery to increase efficiency. The system consists of a small capacity naturally aspirated gasoline powered ICE coupled with a generator. This generator is electrically linked to a battery pack. The ICE also has an exhaust gas turbine (EGT) which is coupled to another generator. This generator is also electrically linked to the battery pack. The model is represented schematically in Figure 2.

The battery pack is split into two sections, say X and Y. In normal operating modes with both the sections of the battery at full charge, the vehicle runs solely on battery power. This power is supplied by one of the halves of the pack, say X. When X reaches a predetermined low state of charge, the power is drawn from the section Y. While power is drawn from section Y, the generator coupled with the engine and the generator coupled with the EGT are turned on and these recharge section X. When section Y reaches a predetermined low SOC, the power is again drawn from section X. and the generators recharge section Y. This cycle allows the battery pack to be charged and utilized simultaneously. This cycle continues till either the vehicle is switched off or the ICE engine runs out of gasoline.

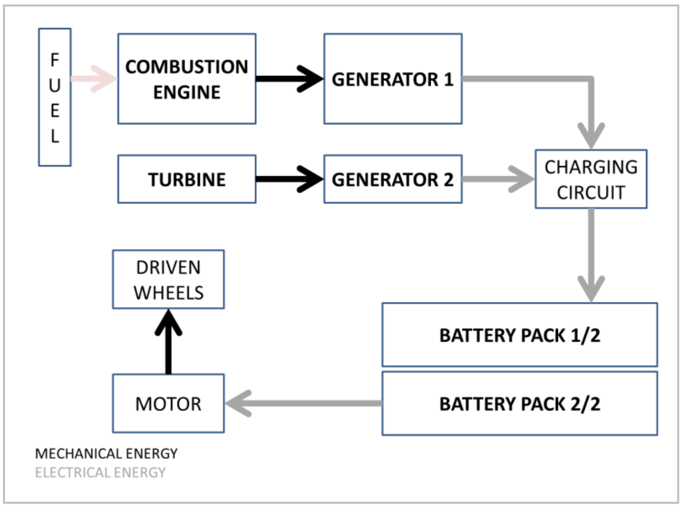

Figure 2 Proposed power flow diagram

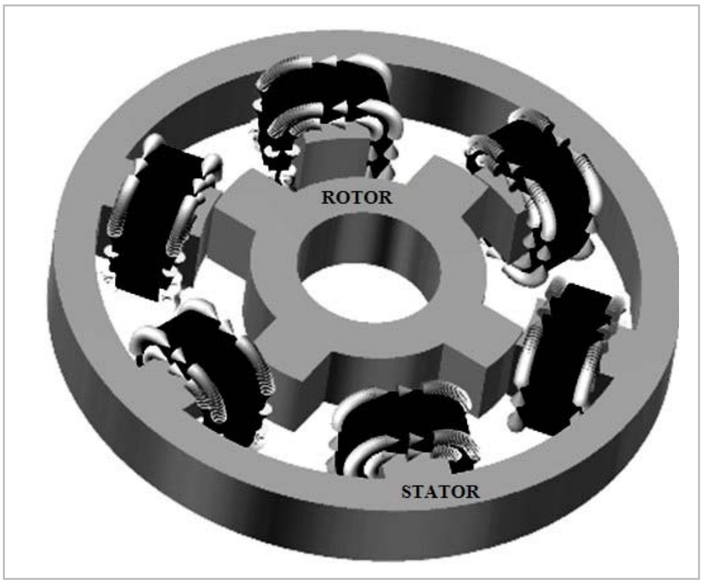

Figure 3 Schematic of a switched reluctance motor

The generator (generator 2 in Figure 2) that converts the mechanical energy of the turbine (driven by exhaust gases) to electricity will be rotating at a relatively higher speed. To provide efficient generation at high speeds, a switched reluctance generator is used. This generator has a very rugged construction and the rotor (rotating component) has no coils around it, this allows high operating speeds. A switched reluctance generator has other advantages like wide speed range of operation, simple construction, ruggedness, easy cooling, simple excitation and high efficiency [10, 11].

Switched reluctance motors are a modified version of stepper motors with fewer poles and they are designed for higher efficiency and wider range of speed. The switched reluctance motors (SRM) have a salient pole stator and rotor like stepper motors. The main advantage of switched reluctance motors is that the rotor has no windings making it very rugged and suited for high speed applications. As all electrical machines the switched reluctance motor will also work reciprocal that is in generating mode [15].

IV. MODELING OF THE SYSTEM

To model the above system and obtain expected figures, the working principle of a turbocharger was used. A schematic of a simple turbocharger is illustrated in figure 4. The proposed system can be visualized as a turbocharger with the compressor and the link between the compressor and the intake manifold being replaced with a generator. The EGT and the coupling between the EGT and the generator is analogous to the EGT in the turbocharger and its link with the compressor.

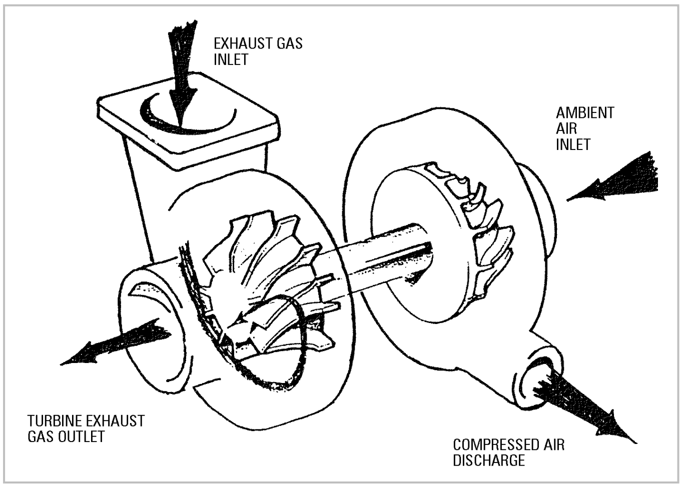

Figure 4 Schematic of a turbocharger

To model the system, the generator coupled with the EGT is replaced with a virtual compressor whose air flow rating is the same as the air flow through the naturally aspirated engine mentioned above. This is done because, unlike the compressor in a turbocharger, the system does not compress any air and hence, the mass flow rating will not increase.

The volume air flow rating of the virtual compressor was calculated using –

$$\dot{V} = N \times V_{eng.} \times \eta_{vol.} \qquad (1)$$

Where

$V_{eng.}$ = volume of the engine in m^3

$\dot{V}$ = volume flow rating of the compressor in m^3 / min

N = engine speed in revolutions per minute

η_{vol} = volumetric efficiency of the engine

The mass flow rating of the virtual compressor was calculated using the equation from [8] –

$$\dot{m} = (P_1 \times \dot{V})/(R \times T_1) \qquad (2)$$

Where

$\dot{m}$ = mass flow rating of the compressor in kg/min

P_1 = inlet pressure of the virtual compressor assumed to be 101325 Pa

R = Gas constant equal to 287 $Jkg^{-1}\ K^{-1}$

T_1 = Inlet temperature assumed to be 298K

Now, the pressure ratio of the compressor, which is the ratio between the final and initial pressure was required. For this, the compressor map of a small turbocharger, namely the Garrett GT1240-C was used. This charts the pressure ratio for the given compressor against the mass flow rate through the compressor in pounds per minute. The compressor map also includes pressure ratios for different efficiencies of the compressor. For this paper's purposes, an efficiency of 74% was assumed as this is approximately the efficiency of a compressor working with airflow well within its operating range.

Now, for calculating the work required by the virtual compressor, we need the temperature of the air after compression. This temperature was found using the thermodynamic equation relating the pressure and temperature for an adiabatic process from [8] –

$$T_2 = T_1 + T_1\ ((P_2/P_1)\text{^}((n-1)/n) - 1) \qquad (3)$$

Where

T_2 = Temperature at outlet of compressor in K

P_2 = Pressure at outlet of compressor

n = Ratio of specific heats assumed to be 1.3 for air

The expression for power required by the compressor is given by [8] –

$$P = (n/(n-1)\ \dot{m}R(T_2 - T_1\ ))/\eta_{comp} \qquad (4)$$

Where

$\eta_{comp.}$ = Efficiency of the compressor assumed to be 74%

Since the power required by the virtual compressor is a measure of the amount of power generated by the EGT, eq. (4) gives the power that can be expected above the engine's output power.

V. RESULTS AND INTERPRETATION

The proposed system was modeled in Matlab using the equations detailed above and using the compressor map for the Garrett GT1240 turbocharger [7]. The engine under consideration was the Volkswagen Lupo FSI with an engine capacity of 1.4 liters and a peak power of 77kW [6]. This engine was chosen based on the design of the Chevrolet Volt which uses a 55kW peak power engine running at premium gasoline for its purposes [9].

The engine under consideration in the system reaches peak torque at approximately 4000 rpm. As this is the point where the engine is at its most efficient, this point of operation was chosen as the desired one. Figure 5 shows the power versus engine speed graph of the Volkswagen Lupo FSI engine through its engine speed range and 12 data points corresponding to the simulation of the proposed system till the chosen optimum speed of 3900 rpm.

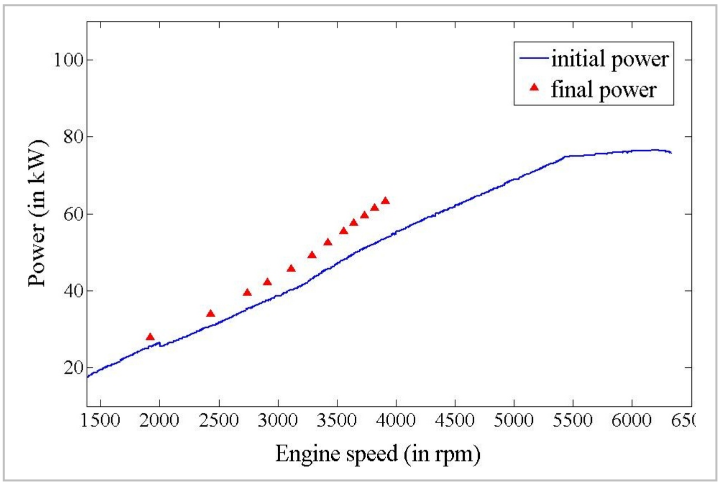

Figure 5 Comparison of the initial and final system

The output power of the engine with the proposed system was found to be significantly higher as seen in Figure 5. The gains over initial power ranged from 9.35% at 1920 rpm to 18.12% at 3907 rpm.

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