Simulation of exhaust gas energy recovery system using turbo-compounding for a motorcycle engine

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Abstract. The project aims to recover the energy from the waste exhaust gas and utilize it for application such as battery charging of hybrid electric vehicles. The concept used for energy recovery is electric turbo-compounding which encompasses a turbine integrated with the exhaust manifold of an automobile. The exhaust gases are allowed to expand through the surface of blades of the turbine imparting the energy which can be seen by rotational action of impeller. This motion is captured by a motor generative unit which then produces electric power. The performance of the exhaust gas energy recovery system is simulated on a 390cc motorcycle engine using MATLAB Simulink. The engine was simulated using standard practical low loading and high loading drive cycles such as FTP72, FTP75 (city driving cycles) and US06 (highway driving cycle). Results from the simulation indicate a considerable amount of energy recovery from the exhaust gases of an engine under the above-mentioned driving cycles. Considering the amount of energy recovered, the next focus is to optimize the current system.

Keywords: Energy recovery, turbine, exhaust gas, motor-generative unit, MATLAB.

1. Introduction
The increasing concern on energy conservation, rising oil prices and focus on reducing emissions is leading to the development of energy-efficient technologies for automobiles at an accelerated pace. The conventional internal combustion engine normally has an efficiency between 25\% and 35\% under optimal conditions. This also signifies that up to 75\% of energy from vehicle fuel combustion is lost as heat. This has led to the emergence of energy recovery systems which increase overall vehicle efficiency by recovering energy which otherwise would be lost as heat. For vehicle applications, designs that require minimal integration are gaining significant interest [1]. There is a wide variety of engineering concepts and designs in the market to maximize the potential of energy recovery from vehicle exhaust. These include Thermoelectric Generation (TEG), where the exhaust flow path has thermoelectric elements to generate electricity. Organic Rankine cycle systems are also being studied, and much research is being done to find a solution for waste heat recovery. In addition to these technologies, a turbo-generator system which generates electrical energy from the exhaust gas has proven as an attractive solution for energy recovery [2]. Another interesting method of energy recovery is turbo compounding which is a mechanism of attaching a turbocharger to the exhaust manifold of an automobile which contains two components, a turbine, which rotates by the action of the incoming flow of pressurized exhaust gas and a compressor connected to the turbine via a shaft, to extract the exceeding power from the turbine and assisting in compressing more airflow at the inlet thereby increasing the...
supply of air during high load request and improving the dynamic response of the engine [3]. There are two ways in which a turbo-compounding can produce an output, first in the form of mechanical energy by coupling a power turbine to the primary turbine, hence called mechanical turbo-compounding, second in the form of electric energy by coupling a motor-generator to the shaft of the primary turbine and hence this method is called electric turbo-compounding. In order to achieve the maximum power extraction from the exhaust gases, many researchers have worked on a low-pressure turbine placed downstream of the main turbocharger. One of the disadvantages of this architecture is that there is a back pressure to the engine that could cause a rise in pumping losses and result in higher fuel consumption.

The following report is mainly based on electric turbo-compounding for low powered gasoline engines where-in a turbine is attached to the exhaust manifold to capture the incoming flow of exhaust gases from a combustion chamber. The compressor is eliminated because, for the low powered engine, there is no need to boost the incoming air as the load on the engine will be relatively less. Based on Faraday's law of induction which states that “the total emf induced in a closed circuit is equal to the time rate of decrease of total magnetic flux linking the circuit”, the shaft of the turbine is connected to a generator which converts mechanical energy to electrical energy. The pressurized exhaust gas produced as the result of combustion expands through the blades of the impeller inside a turbine causing a rotational motion. This motion captured by the generator via the turbine shaft starts producing electrical energy which can be stored in a battery or can be used for various applications.

2. Literature Survey

The aim is to simulate an exhaust gas energy recovery system which can be used to charge the auxiliary battery through the method of electric turbo-compounding which involves the integration of a motor generative unit with a turbocharged engine. One such method was proposed by Weilin Zhuge et al. [4] to optimize the electric turbo-compounding for a gasoline engine with a fixed geometry turbine (FGT). The system comprised of a turbo-generator placed parallel with the turbocharger. Throttle-1 and throttle-2 control the exhaust gas flow distribution between the turbocharger and turbo-generator. The position of FGT can be referred from figure 1. At low engine load, the throttle-1 would be partially or full closed to transfer the exhaust energy to the power turbine. At low engine speed, the throttle-2 would partly or fully close to guaranteeing enough energy flow through turbocharger. Their system was simulated under two drive cycles US06 and FTP75, producing electric power of 1.01 kW and 0.266 kW respectively.

![Figure 1. The positioning of the fixed geometry turbine with respect to engine exhaust [4].](image)

M. Michon et al. [5] tested a system which comprised of a turbine, attached to the exhaust manifold of an engine. A switched reluctance motor was connected to the turbine to convert the mechanical energy to electrical energy, as shown in figure 2. To regulate the exhaust mass flow rate through the turbine, there is a wastegate. Also, the wastegate helps to protect the system in the event of a failure in the generator or the power supply to the throttle actuator. The complete turbo-generator system was tested on the cold air compressor test rig. For initial testing and verification, an air-compressor was used to run the turbine. The system was successfully tested up to 1.8kW electrical output power at 65000 rpm.
Chuang Yu et al. [6] proposed a thermoelectric waste heat energy recovery system for internal combustion engine automobiles, including gasoline vehicles and hybrid electric vehicles. They aimed to use the heat energy of automotive exhaust and convert it to electrical energy using a thermoelectric generator [TEG]. A power converter was used to regulate the charge to the battery using maximum power point tracking. Thermoelectricity was generated using the Seebeck effect, which states that electricity can be generated if there is a temperature difference between the two surfaces of a material. The flow of energy was as follows, an exhaust gas system, a heat exchanger, a TEG system, a power converter system and a battery pack. The maximum power obtained was 34.8 W on a duty cycle at a temperature of 200 °C. They also suggested that there should be more than one TEG device connected in series to obtain more power. Figure 3 can be referred to know the positioning of a TEG device.

Andre Haughton et al. [7] developed the Turbine-generator Integrated Gas Energy Recovery System (TIGERS) which consisted of an impeller, a volute and a separate back-plate, angular contact grease-filled bearings, which were in direct contact with exhaust gas which could reach up to a temperature of 900 °C. A coolant system was also developed for the TIGERS because of the bearings were operating between the temperature range of 80 - 105 °C with a flow rate of up to 6 l/min and a minimal pressure drop. Figure 4 shows a bypass valve being introduced for both safety and performance control. The set-up was tested on a dynamometer, and the following observations were made, for a turbine speed of 45000 RPM, the device generated power of 1.2 kW and 0.6 kW at coolant temperatures of 80 °C and 105 °C respectively.
Albert Boretti [8] focused on the study of the performance of the Motor Generator Unit-Heat (MGU-H) system as used in a Formula 1 car applied to the turbocharger of a gasoline hybrid electric passenger car. The author considers the steady operation of a turbocharged engine with an MGU-H system and the performance parameters like total efficiency (the ratio of engine crankshaft power plus the turbocharger shaft power to the fuel flow power) and total brake mean effective pressure (BMEP). The MGU-H system consists of a motor-generator unit installed either on the side of the compressor or between the compressor and the turbine. Figure 5 demonstrates a series arrangement of MGU with a turbo-charger. When the turbine power exceeds the power needed by the compressor at high speeds, the MGU-H system recovers the energy by producing electric power to charge the battery. The MGU-H system increases the total efficiency and allows to control the turbocharger operating points. The use of an MGU-H during steady operation shows an improvement in total fuel conversion efficiency and an increase of 4–5% in total efficiency. This system also helps to increase the brake mean effective pressure (BMEP) by increasing the boost pressure. The system also helps reduce turbo lag considerably during accelerations. The author concludes that from turbocharging with MGU-H, both performances and fuel economy will increase and it will definitely benefit road Hybrid Electric Vehicles (HEV).

3. System Modelling
As discussed in the introduction, the modelling is done considering the physical environment through which vehicles manoeuvre. The input for the system is throttle response of the driver or engine rpm whichever is available, and the output is torque obtained for different values of input and its subsequent power generation. The overall system consists of two subsystems, first an IC engine, second a motor generative unit. The mechanical aspects of the system are modelled in the first subsystem, and the electrical aspects are modelled in the second subsystem. With reference to figure 6, a drive cycle is acting as an input parameter to the IC engine, which is a mechanical subsystem. The output of the first subsystem is fed as input to the second subsystem.
3.1. Mechanical subsystem

This subsystem consists of automotive powertrain components. Literature survey helped to identify various blocks required, as from the real-time point of view and these blocks were connected via virtual mechanical linkages. The various blocks include a core gasoline powered engine, a throttle body, an intake manifold, an exhaust manifold, a turbocharger, an exhaust pipe, a muffler and a mechanical shaft. Figure 7 helps in understanding the system.

The SI core engine block implements a spark-ignition (SI) engine from intake to exhaust port. Different parameters govern the working of this block such as fuel injector pulse width, spark advance, intake cam-phase angle, exhaust cam-phase angle, ambient pressure, input engine speed, engine coolant temperature and air intake system. Most of the parameters were obtained when data was logged from a real engine. The input engine speed was given through city drive cycles such as FTP72, FTP75 and US06, which are the standard drive cycles. The different parameters on which the drive cycle was built is displayed in table 1.

![Figure 6. Overview of Electric Turbo-Compounding system.](image)

![Figure 7. Modelling of Mechanical subsystem.](image)
Table 1. Parameters of drive cycles.

|          | Total distance | Total duration | Average speed  | Maximum speed |
|----------|----------------|----------------|----------------|---------------|
| FTP-72   | 12.07 km       | 1369 s         | 31.50 kmph     | 91.20 kmph    |
| FTP-75   | 17.77 km       | 1877 s         | 34.12 kmph     | 91.25 kmph    |
| US06     | 12.80 km       | 596 s          | 77.90 kmph     | 129.2 kmph    |

The air intake system of the model consists of a throttle body to draw air from the environment to the intake manifold and then to engine. For initial condition, the throttle plate was 98% closed for idle engine speed. The obtained output parameter, the exhaust mass flow rate was given as input to further model of the turbine, allowing the exhaust gas to expand through the blades of an impeller to convert it into rotational motion. This kinetic energy is captured by the motor generative unit (electrical subsystem) and convert it to electric energy.

3.2. Electrical subsystem

This subsystem consists of electrical components assembled in an electric circuit to convert mechanical energy into electrical energy and is called motor generative unit. Figure 8 depicts the electrical circuit, which constitutes a motor generative unit. Electric blocks from simscape block set were used to model the motor generative unit. The different blocks involved here are an ideal angular velocity source, an ideal torque sensor, a DC motor, a load, voltage sensor, current sensor, mechanical and electrical rotational reference.

![Figure 8. Modelling of the electrical subsystem.](image)

An ideal source of angular velocity is the one that generates velocity differential at its terminals, proportional to the input physical signal. The output speed of the turbine is fed to angular velocity source to obtain its velocity differential. The ideal torque sensor is a device that converts a variable, passing through the sensor into a control signal proportional to the torque. The sensor is ideal because it does not account for inertia, friction, delays, energy consumption. The velocity differential obtained is converted to a variable through the ideal torque sensor. The variable obtained serves as an input to the DC motor shaft. The input signal starts rotating the rotor, which is eventually connected to the shaft. The carbon brush connected to commutators helps to capture this voltage. A load (in the current system
a resistor of 100 ohms) connected across the terminals of the carbon brushes helps to calculate the amount of power generated by connecting a voltage sensor across the load and by measuring the current through the circuit using a current sensor. Integration of simscape block set with Simulink block is done through a PS-S converter.

4. Observation and Results
When the model was simulated against all the three drive cycles, the graphs were obtained and are analyzed. Two graphs of the vehicle’s velocity and exhaust mass flow rate for city drive cycle FTP-75 is plotted below with respect to time.

![Graph of the velocity of the vehicle (m/s) vs time (s) for FTP-75](image1)

**Figure 9.** Graph of the velocity of the vehicle (m/s) vs time (s) for FTP-75

![Graph of mass flow rate (kg/s) vs time (s) for FTP-75](image2)

**Figure 10.** Graph of mass flow rate (kg/s) vs time (s) for FTP-75

From the figure 9, we can observe that the maximum speed attained by the vehicle was 26 m/s (94 kmph) at two instances, i.e. approximately at 210th second and 2210th second for which its subsequent mass flow rate was around 4.5e-3 kg/s (refer figure 10). For the rest of the duration, the speed was averaged at 10 m/s (36 kmph). The engine was kept idling between 1350th second and 1900th second to record the idle case behaviour of the mass flow rate.
Figure 11. The cumulative variation of power for the FTP-75 drive cycle.

Figure 12. The cumulative variation of power for FTP-72 drive cycle.
Figure 13. The cumulative variation of power for US06 drive cycle.

From figure 11, 12, 13, it can be observed that the power generated is the function of exhaust flow rate, which in turn is a function of engine speed. Also, the relation between engine speed and brake torque produced can be referred from the respective figures. The output values for different input drive cycles are tabulated in table 2.

Table 2. Comparison of various parameters for all the three drive cycles

| Parameter                           | FTP-72 | FTP-75 | US06 |
|-------------------------------------|--------|--------|------|
| Run time (s)                        | 1372   | 2474   | 600  |
| Average exhaust flow rate (kg/s)    | 3.5e-3 | 3.6e-3 | 4.4e-3 |
| Average turbine shaft speed (rpm)   | 40,620 | 49,740 | 39,740 |
| Exhaust power (W)                   | 3576   | 3659   | 4901 |
| Power generated (W)                 | 98.65  | 134.7  | 97.47 |
| Energy recovered (%)                | 2.75   | 3.68   | 1.98 |

The simulation was conducted in MATLAB Simulink for a vehicle of engine displacement 0.000371 m\(^3\) powered 30.4 kW at 9600 rpm with variable throttle response from different city drive cycles to generate power. The system was able to generate a maximum of 134.7 W of energy for drive cycle FTP-75 which accounts for 3.68% of total exhaust energy generated during combustion for a drive time of 42 minutes. Also, the other two drive cycles result show a positive trend in recovering energy, i.e. 2.75%
recovery for FTP-72 and 1.98% recovery for US06, respectively. The turbine shaft attained a maximum speed of 86,000 rpm. Therefore, the speed of the shaft would appear to be less than the maximum value when compared with a real-time application on the same engine due to the inertia factor.

5. Conclusion
The results from the simulation were promising to say that the electric turbo-compounding concept would greatly help in recovering the energy from the wasted exhaust gas. There was also an increase in the overall efficiency of the engine by 0.4%. The system can, not just be integrated with gasoline powered engine but also with hybrid commercial vehicles.

6. References
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