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Motor-Generator Unit (MGU) Assisted Turbocharger for Improved Turbocharging and Environmental Performance in Commercial and Passenger Vehicles

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***Abstract* — *Approximately one third of fuel energy is lost as heat through the exhaust system. So any small reduction in this waste heat can lead to significant reduction in fuel consumption. Reduction in fuel consumption will lead to less emissions from automobile which in turn will satisfy the pollution norms. If automotive engines are to achieve better environmental or eco-friendly properties and drivability then they must be equipped with more advanced systems of operation control. Electrical operation systems are now being incorporated in engine design for this purpose.*

This paper deals with an electrically assisted turbocharger in automobiles with a high speed motor-generator unit built in. When operating in the low-speed engine mode, this turbo can achieve better combustion, pure exhaust gas, enhanced torque response, and torque advancement with motor assistance. In the high-speed engine mode, it can operate with very high efficiency by achieving regeneration of electric energy in excess of the exhaust gas energy.

Keywords— 3 – Phase AC Synchronous Generator, Inverter, HERS, Hybrid Turbo.

I. INTRODUCTION

Recent trend is to use the deployable sources of energy into useful work in order to reduce the rate of consumption of fossil fuels as well as environmental pollution. Internal Combustion Engines (ICE) are the top consumers of fossil fuels all around the globe. In ICE out of the 100% fuel energy supplied only 30-40% of energy is used to do mechanical work or provide power to the engine, remaining energy is carried away by exhaust gases, cooling system, and other accessories of the engine. Most of the heat energy in engine is expelled into the environment leading into increase of entropy and serious environmental pollution. It also results in damping of greenhouse gases in the environment leading to increase in global temperature. Also certain elements in exhaust gases due to incomplete or inefficient combustion are carcinogenic which affect the human health drastically. The recovery and utilization of heat energy not only conserves fossil fuel but also solve the serious problems of environmental pollution. As the no of automobiles are increasing at faster rate heat energy recovery techniques will reduce overall energy requirement and also the impact on global warming. Main aim of turbocharging is to downsize the engine that is to increase the power output , a wide rpm range with constantly high torque and reduction of fuel consumption without increasing the size of engine. But the major disadvantage of turbocharged engines is the turbo lag regarding the mean effective pressure built up at low rpm. In case of a load step taking place at low engine speeds (1500 to 2000 rpm) , only a low enthalphy gradient is available to the turbine for the compressor capacity and power loss. This results in low power available to accelerate the turbocharger. This incomplete charging process of a turbocharger not only affects the drivability but also the energy consumption and pollution. Even in modern turbocharged engines large portion of exhaust gas goes waste into the environment during its dynamic operation.

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Table 1 : Heat balance sheet for SI engine[1]

Credit	%	Debit	%
Heat supplied by combustion of fuel	100%	Brake Power	21% to 28%
		Heat carried away by cooling Water	12% to 27%
		Heat carried away by exhaust gases	30% to 55%
		Unaccounted Heat loss (Radiation loss, friction losses, losses due to incomplete combustion	3% to 55%

Table.2: Heat balance sheet For CI engine[1]

Credit	%	Debit	%
Heat supplied by combustion of fuel	100%	Brake Power	29% to 42%
		Heat carried away by cooling Water	15% to 35 %
		Heat carried away by exhaust gases	25% to 45%
		Unaccounted Heat loss (Radiation loss, friction losses)	0% to 21%

The electrical load of a commercial vehicle is also increasing due to improvements in driving performance and comfort. Electrical loads are of three types namely continuous loads, prolonged loads, and intermittent loads. The clear overview is given in tables 3, 4 and 5

Table.3: Intermittent loads[1]

Intermittent Loads:	Power (W)	Current(A) 14 V	28 V
Heater	**50**	**3.5**	**2.0**
Indicators	**50**	**3.5**	**2.0**
Brake lights	**40**	**3.0**	**1.5**
Front wipers	**80**	**6.0**	**3.0**
Rear wipers	**50**	**3.5**	**2.0**
Electric windows	**150**	**11.0**	**5.5**
Radiator cooling fan	**150**	**11.0**	**5.5**
Heater blower motor	**80**	**6.0**	**3.0**
Heated rear window	**120**	**9.0**	**4.5**
Interior lights	**10**	**1.0**	**0.5**
Horns	**40**	**3.0**	**1.5**
Rear lights	**40**	**3.0**	**1.5**
Reversing lights	**40**	**3.0**	**1.5**
Auxiliary fog/spot lamps	**110**	**8.0**	**4.0**
Cigarette lighter	**100**	**7.0**	**3.5**
Headlight wash wipe	**100**	**7.0**	**3.5**
Seat movement	**150**	**11.0**	**5.5**
Seat heater	**200**	**14.0**	**7.0**
Sun-roof motor	**150**	**11.0**	**5.5**
Electric mirrors	**10**	**1.0**	**0.5**
Total (approximately)	**1.7 kW**	**126A**	**65A**

Table 4: Continuous Loads[1]

Continuous Loads:	***Power (W)***	***Current(A) 14V***	***28V***
Ignition	*30*	*2*	*1*
Fuel Injection	*70*	*5.0*	*2.5*
Fuel Pump	*70*	*5.0*	*2.5*
Instruments	*10*	*1.0*	*0.5*
Total	*180*	*13*	*6.5*

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Table 5 : Prolonged Loads[1]

Prolonged Loads:	Power (W)	Current(A) 14V	28V
Side and tail lights	**30**	**2.0**	**1.0**
Number plate lights	**10**	**1.0**	**0.5**
Headlights main dip beam	**180**	**13.5**	**6.5**
Dashboard lights	**25**	**2.0**	**1.0**
Radio/Cassettes/CD	**15**	**1.0**	**0.5**
Total	**260**	**19.5**	**9.5**

In order to meet these electrical energy demands, efficient engine performance as well as turbocharger performance and reduced fuel consumption in automobiles the MGU-H assisted Turbocharging is proposed. It makes a lot of sense because automakers can downsize engine displacement and can acquire higher power and efficiency in a eco-friendly manner. The MGU-H assisted turbocharging is a very efficient way for automakers to achieve better engine performance, minimum emissions, harvesting waste heat and reduced fuel consumption in one package [1].

II. MGU-H ASSISTED TURBOCHARGED ENGINE

In normally aspirated IC engines during intake stroke the charge in case of SI engines and air in case of CI engines is sucked into the engine by pressure difference caused due to downward stroke of the piston. The amount of air actually aspirated compared to theoretical amount of air available in the engine if the engine could maintain atmospheric pressure is called volumetric efficiency. The objective of the turbocharger is to improve engine's volumetric efficiency by increasing density of intake charge. The turbocharger's compressor draws in ambient air and compresses it and deliver to the intake manifold at high pressure. This results in a greater mass and density of air entering the cylinders on each intake stroke. The power needed to drive the centrifugal compressor is obtained from the kinetic & heat energy of the engine's exhaust gases. In the MGU-H assisted turbocharger exhaust energy is converted to mechanical energy of the shaft by an exhaust turbine. The mechanical energy from the turbine is then used to drive the compressor, and also the MGU-H (see below). At its fastest point the turbocharger is rotating over 1,50,000 revolutions per minute, or over 2500 revolutions per second the pressures and temperatures generated will be enormous. Some of the energy recovered from the exhaust gases will be passed on to the MGU-H and converted to electrical energy that will be stored in energy storage systems and can later be re-deployed to prevent the turbo lag at lower rpms or under too much braking [1].

III. MOTOR-GENERATOR UNIT AND POWER ELECTRONICS

A motor generator unit is simply an electrical machine. When operating as a motor, the MGU converts electrical energy into mechanical energy. When it operates as a generator the MGU converts mechanical energy into electrical energy [1].

3.1 Ultra High Speed Motor Generator

A permanent magnet synchronous type is adopted as the ultra high speed motor generator. It has a small size rotor and stator with concentration winding used to reduce size of the winding. This concentration winding is of 6-slot structure to reduce the rotor eddy current loss [4].

3.2 Battery

A energy storage devices (Battery) are used to store the energy. Research is going on to replace battery by super capacitor for quick charging and discharging the MGU [4].

3.3 Energy Recovery System Control Unit (ERS)

ERS is a computer which is the brain of this power unit. It controls how the energy in the power unit is used that is when to convert mechanical energy into electrical energy and electrical energy into mechanical energy. In short it controls the mode change of MGU from generating to motoring. Its software determines how well the MGU perform under constantly and rapidly changing environment and driving conditions. Battery operates using DC. MGU operates using AC current. The ERS control unit includes AC/DC and DC/AC converters to convert electricity between battery and MGU-H. The converters are not simple rectifier with diodes but a synchronous rectifier with switching devices that is it consists of Insulated Gate Bipolar Transistor which is a three terminal power semiconductor device that combines high efficiency and fast switching. An IGBT cell is constructed similarly to a n-channel MOSFET except the n+ drain is replaced with a p+ collector layer, thus forming a vertical PNP Bipolar Junction Transistor with the surface n-channel MOSFET [4].

3.4 Operating modes

3.4.1 Charging mode : At high engine speed or rpm there is more amount of energy generated by the turbine as the flow rate and volume of exhaust gases is enormous at high

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speeds. Such high flow rate drives the turbine at faster rate. The rotational energy or mechanical energy produced by turbine is very larger than required by the compressor. So remaining energy is fed to MGU. First the motor generator converts this mechanical energy into electrical energy. It gives output in AC which goes to AC/DC converter in ERS control unit. After conversion in DC it goes to the battery and this electrical energy is stored. This excess energy is used to recharge the energy storage or used to power some electrical loads shown in tables 3,4 and 5 [2].

3.4.2 Discharging mode: When the driver depresses the throttle , the ERS control unit discharges the battery and provide AC to the MGU through DC/AC converter. Then the computer changes the mode of MGU to motoring and hence MGU acting as a motor converts electrical power to mechanical power which is used to power the compressor. This rate of acceleration eliminates turbo lag which is a curse for performance of standard turbocharged engines**.** Turbo lag is a phenomenon experienced under braking when the turbocharger speed slows as a lower volume of gas is produced. In an MGU assisted turbocharged engine ECU can deliver precise fuel flow rate for complete combustion more accurately. This is achieved by direct controlling the air flow rate and boost pressure via control of the compressor speed [2].

The proposed Motor Generator Unit Assisted Turbocharger [1]

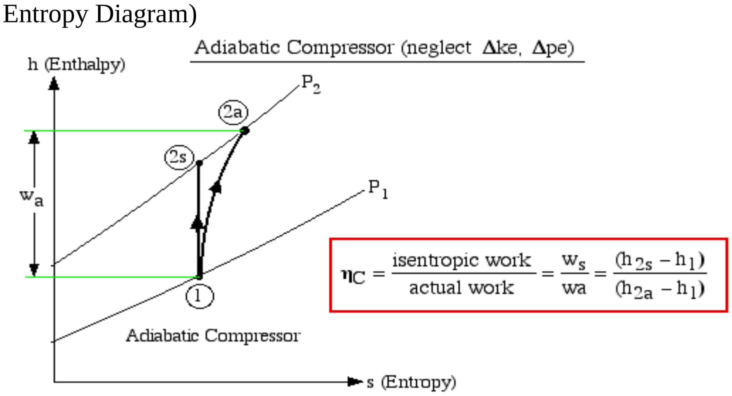
Fig.1: MGU Assisted Turbocharger

IV. NOMENCLATURE

γ - Compression Ratio
η - Isentropic Efficiency
C_{pa} - Specific Heat Capacity of Air at constant pressure [kJ/kg K]
C_{pg} - Specific Heat Capacity of Gas at constant pressure [kJ/kg K]
$\dot{m}_a$ - Mass flow rate of air [kg/s]
$\dot{m}_f$ - Mass flow rate of fuel [kg/s]
M - Torque
$\dot{W}$ - Work or Energy flow rate [W]
T - Temperature [K]
C - Compressor
T - Turbine
P - Power [KW]
I - Inertia [kg/m^2]
ω - Turbocharger rotational speed [rad/s]
t - Time [s]
V_t - Total Displacement [m^3]
n - ICE rotational speed [rpm]
p - Pressure [Pa]
R - Gas constant [kJ/kg K]
0 - ICE inlet condition
MGU-H - Motor – Generator Unit – Heat
h - Enthalphy

V. CALCULATIONS

The proposed MGU-H model is based on these calculations:-
Steady flow energy equation is given by
$\dot{W} = \dot{m}\ [\ h_{out} - h_{in}\ ]$
h-S diagram for the compressor is given as (Enthalphy-Entropy Diagram)



η_C = Isentropic Work / Actual Work = $\dot{W}_s / \dot{W}_a$
$\dot{W}_a = \dot{W}_s / \eta_C$
$= [\ \dot{m}_a C_{pa} (T_{2s} - T_1)] / \eta_C$
$= \dot{m}_a C_{pa} T_1 / \eta_C\ (T_{2s} / T_1 - 1)$
As it is a isentropic process
$T_{2s} / T_1 = (p_{2s} / p_1)^{\gamma-1/\gamma}$
$P_C = \dot{m}_a C_{pa} T_1 / \eta_C\ [(p_{2s} / p_1)_C^{\gamma-1/\gamma} - 1]$ (1)
h-S diagram for turbine is given by (Enthalphy- Entropy Diagram)

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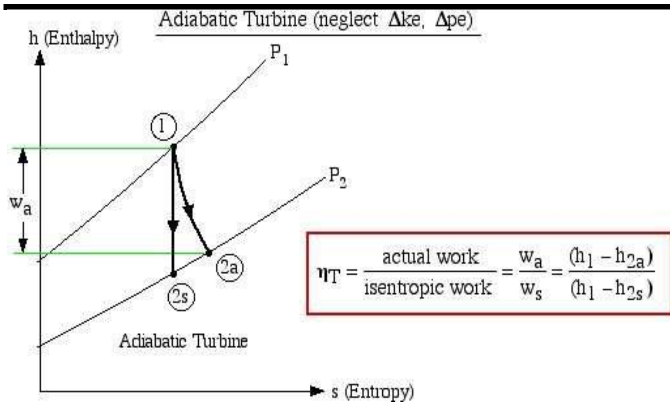

η_T = Actual Work / Isentropic Work = $\dot{W}_a / \dot{W}_s$

$\dot{W}_a = \dot{W}_s * \eta_T$

$= (\dot{m}_a + \dot{m}_f)\, \eta_T\, C_{pg}(T_1 - T_{2s})$

$= (\dot{m}_a + \dot{m}_f)\, \eta_T\, C_{pg}\, T_1\, (1 - T_{2s} / T_1)$

As it is a isentropic process

$T_{2s} / T_1 = (p_{2s} / p_1)^{\gamma\text{-}1 / \gamma}$

$P_T = (\dot{m}_a + \dot{m}_f)\, \eta_T\, C_{pg}\, T_1\, [\, 1 - (p_{2s} / p_1)_T{}^{\gamma\text{-}1 / \gamma}\,]$ (2)

From equations (1) and (2) we get the power of turbine and compressor.

Now let $P_{MGU\text{-}H}$ be the power provided or absorbed by the Motor-Generator Unit – Heat Machine

Therefore, the equation becomes

$P_T - P_C \pm P_{MGU\text{-}H} = T\, \omega = I\, (d\, \omega /dt)\, \omega$ (3)

Equation (3) can be written in terms of torque

$M_T - M_C \pm M_{MGU\text{-}H} = I\, (d\, \omega /dt)$ (4)

Volumetric Efficiency is given by

$\eta_V = V_a / V_t$

$V_a = \eta_V\, V_t$

$= \eta_V * \pi/4 * D^2 * L * x * n /120$ (5)

Where D is bore diameter, L is stroke length and x is no of cylinders.

Compressor inlet conditions are :-

$p_1 V_1 = \dot{m}_1\, R\, T_1$ (6)

Compressor outlet conditions are :-

$p_2 V_2 = \dot{m}_2\, R\, T_2$ (7)

Assume constant volume and perfect intercooling. So dividing equation (7) by (6) we get

$p_2 / p_1 = \dot{m}_2 / \dot{m}_1$ (p_2 / p_1 = pressure ratio of compressor)

Also $\dot{m}_2 = \dot{m}_a = \rho\, V_a\, p_2 / p_1$

$=[(\, p_a / RT_0\,) * (\, p_2 / p_1) * \eta_V * \pi/4 * D^2 * L * x * (n /120)\,]$ (8)

Equation (8) gives the mass flow rate of air aspirated by the IC Engine in function of compressor pressure ratio for the different operational conditions. Thus from all these calculations and the derivations of the above equations we can conclude that $P_{MGU\text{-}H}$ is the power consumed or generated by from the exhaust gases by harvesting the waste heat energy with the use of Motor-Generator Unit – Heat assisted Turbocharger [1] .

Some Real Time Engines of top automobile manufacturers with MGU-H :

Fig.2: Mercedes Benz Engine [5]

Fig 3: Renault F1 Engine [3]

VI. CONCLUSION

So far this technology is being used in Formula One Racing cars in order to improve their performance in the race. This MGU-H unit assisted Turbocharger is the secret of such phenomenal performance with reduced fuel consumption of the F1 racing cars. This technology is not yet applied to the commercial vehicles and passenger cars. So if this technology is introduced in commercial and passenger vehicles then it will solve major environmental problems that are caused by these vehicles. Also it will be easy for the automobile manufacturers to meet the stringent pollution norms. This technology can bring up revolution in the automotive industry by making every passenger and commercial vehicle eco-friendly. Therefore I hope that this advanced technology is used in the future for commercial and passenger vehicles to ensure better engine performance, reduced fuel consumption, harvesting waste heat energy, excellent environmental performance and the pleasant comfortable drive.

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