

# **Motor-Generator Unit (MGU) Assisted Turbocharger for Heat Energy Recovering and Improved Turbocharging In Commercial Vehicles**

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**ABSTRACT:** Approximately one third of fuel energy to an internal combustion engine is lost as heat through the exhaust system, even a small reduction in waste heat lead to significant reduction in fuel consumption. If automotive engines are to achieve better environmental properties and drivability, they must be equipped with more advanced systems for operation control. Electrical operation systems are now being incorporated in engine designs for this purpose.

This paper deals with an electrically assisted turbocharger in commercial vehicles with a high speed Motor Generator Unit (MGU) built in. When operating in the low-speed engine mode, this turbo can achieve better combustion, purer exhaust gas, improved torque response, and torque enhancements with motor assistance. In the high-speed engine mode, it can operate with very high efficiency by achieving regeneration of electric power in excess of the exhaust gas energy.

**KEYWORDS:** Motor-Generator Unit - Heat (MGU-H), HERS, Commercial vehicle, assisted turbocharging, hybrid turbo.

## **I. INTRODUCTION**

Recent trend is about the best ways of using the deployable sources of energy into useful work in order to reduce the rate of consumption of fossil fuel as well as pollution. Out of all the available sources, the internal combustion engines are the major consumer of fossil fuel around the globe. The Internal Combustion Engine has been a primary power source for automobiles and automotives over the past century. Out of the total heat supplied to the engine in the form of fuel, approximately, 30 to 40% is converted into useful mechanical work (shown in table 1). The remaining heat is expelled to the environment through exhaust gases and engine cooling systems, resulting in to entropy rise and serious environmental pollution, so it is required to utilized waste heat into useful work. The recovery and utilization of waste heat not only conserves fuel, usually fossil fuel but also reduces the amount of waste heat and greenhouse gases damped to environment. It is imperative that serious and concrete effort should be launched for conserving this energy through exhaust heat recovery techniques. Such a waste heat recovery would ultimately reduce the overall energy requirement and also the impact on global warming [1].

The main targets in developing combustion engines actually are to improve transient behaviour combined with high output, a wide rpm range with constantly high torque and a reduction of fuel consumption. To achieve these targets there is no way around an adequate turbocharging system .The major problem of all turbocharged combustion engines is their delayed response (turbo lag) regarding the mean effective pressure build-up at low rpm. With turbochargers, the charging process is only coupled to the internal combustion engine on the thermodynamic level. On the one hand this offers the advantage that the exhaust gas energy can be utilised, on the other hand the disadvantage that depending on the load point in the characteristic field, and the turbocharger speeds vary significantly.

In case of a load step taking place at low engine speeds (1500 to 2000 rpm), only a low enthalpy gradient is available to the turbine for the compressor capacity and power loss. This results in low available power to accelerate the turbocharger to the stationary endpoint. This incomplete charging process again does not only negatively influence the

driveability but also the energy consumption as well as the pollutant emissions. Even with modern turbocharged engines, a large portion of the gas escaping in the driving cycle is emitted during dynamic operating phases [2].

ENGINE	BRAKE LOAD EFFICIENCY	LOSS TO COOLING WATER	LOSS TO EXHAUST	OTHER LOSSES, FRICTION LOSSES AND LOSS DUE TO INCOMPLETE COMBUSTION
GASOLINE ENGINE (SI-ENGINE)	21% TO 28%	12% TO 27%	30% TO 55%	3% TO 55% (INCOMPLETE COMBUSTION LOSS 0 TO 45%)
DIESEL ENGINE (CI-ENGINE)	29% TO 42%	15% TO 35%	25% TO 45%	0% TO 21% (INCOMPLETE COMBUSTION LOSS 0 TO 5%)

**Table 1: Heat balance sheet of an IC engine**

And also, the electric load of a commercial vehicle is increasing due to improvements in driving performance and comfort. These electrical loads are of three types namely continuous loads, prolonged loads and intermittent loads. The clear overview of various electrical loads is shown in the following tables 2, 3 & 4. [12].

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
<b>Total (approximately)</b>	<b>1.7 kW</b>	<b>126A</b>	<b>65A</b>

**Table 2**

Continuous loads:	Power (W)	Current(A)	
		14 V	28 V
Ignition	30	2.0	1.0
Fuel injection	70	5.0	2.5
Fuel pump	70	5.0	2.5
Instruments	10	1.0	0.5
<b>Total</b>	<b>180</b>	<b>13.0</b>	<b>6.5</b>

**Table 3**

Prolonged loads:	Power (W)	Current(A)	
		14 V	28 V
Side and tall 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
<b>Total</b>	<b>260</b>	<b>19.5</b>	<b>9.5</b>

**Table 4**

In order to meet the electrical energy demands, better engine performance and reduced fuel consumption in commercial vehicles the MGU-H assisted Turbocharging is proposed. It makes a lot of sense because automakers can downsize engine displacement and achieve the same power and efficiency compared with larger naturally aspirated engines. The MGU-H assisted turbocharging is a very efficient way for automakers to make a smaller displacement IC engine with better engine performance, minimum emissions, harvesting waste heat and reduced fuel consumption [10].

**NOMENCLATURE:**

$\beta$	Compression Ratio [-]	Subscripts:	
$\eta$	Isentropic Efficiency [-]	0	ICE inlet conditions
$C_p$	Specific Heat Capacity [kJ/kg K]	a	Air
ICE	Internal Combustion engine	C	Compressor
J	Inertia [kg /m <sup>2</sup> ]	e	Exhaust
k	Isentropic Exponent [-]	f	Fuel
$\lambda_v$	Volumetric Efficiency [-]	T	Turbine
$\dot{m}_a$	Mass flow rate [kg/s]		
M	Torque [Nm]		
MGU-H	Motor-Generator Unit – Heat		
n	ICE rotational speed [r/min]		
p	Pressure [Pa]		
P	Power [kW]		
R	Gas Constant [kJ/kg K]		
T	Temperature [K]		
$\omega$	Turbocharger rotational speed [rad/s]		
t	Time [s]		
$V_t$	Displacement [m <sup>3</sup> ]		

**II. MGU-H ASSISTED TURBOCHARGED ENGINE**

In normally aspirated piston engines, intake gases are "pushed" into the engine by atmospheric pressure filling the volumetric void caused by the downward stroke of the piston (which creates a low-pressure area), similar to drawing liquid using a syringe. The amount of air actually inspired, compared to the theoretical amount if the engine could maintain atmospheric pressure, is called volumetric efficiency. The objective of a turbocharger is to improve an engine's volumetric efficiency by increasing density of the intake charge. [3]

The turbocharger's compressor draws in ambient air and compresses it before it enters into the intake manifold at increased pressure. This results in a greater mass of air entering the cylinders on each intake stroke. The power needed to spin the centrifugal compressor is derived from the kinetic energy of the engine's exhaust gases.

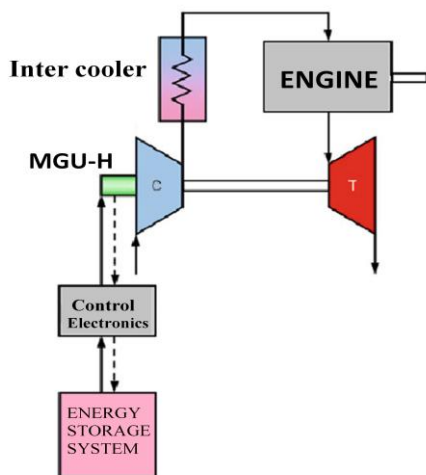
In the MGU-H assisted turbocharger exhaust energy is converted to mechanical shaft power by an exhaust turbine. The mechanical power from the turbine is then used to drive the compressor, and also the MGU-H (see below). At its fastest point the turbocharger is rotating over 100,000 revolutions per minute, or over 1,500 times per second, so the pressures and temperatures generated will be enormous. Some of the energy recovered from the exhaust will be passed on to the MGU-H and converted to electrical energy that will be stored in storage systems and can later be re-deployed to prevent the turbo lag too much under braking. The additional electrical energy could be used to power more advanced engine technologies, such as electro-magnetic valve actuation, electric intake charge cooling and electric-powered super-charging or electrical exhaust after-treatment. [11]

Fig 1 shows the schematic layout of the proposed model of MGU-H assisted turbocharged engine in commercial vehicles.

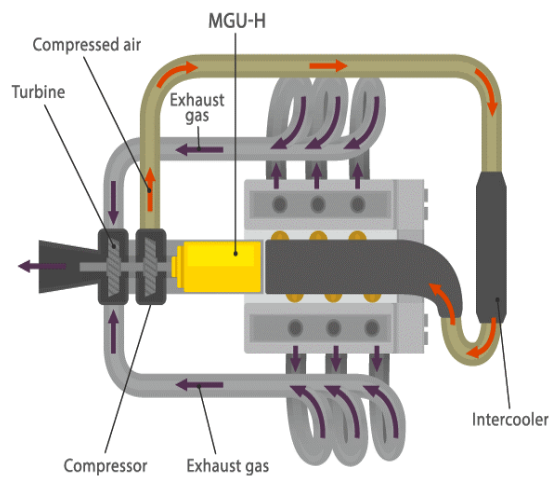
The main components of this engine include [7]:-

- Internal Combustion Engine (ICE)

- Turbine
- Compressor
- MGU-H
- Power and control electronics (ECU)
- Energy storage system



**Fig: 1 MGU-H assisted engine**

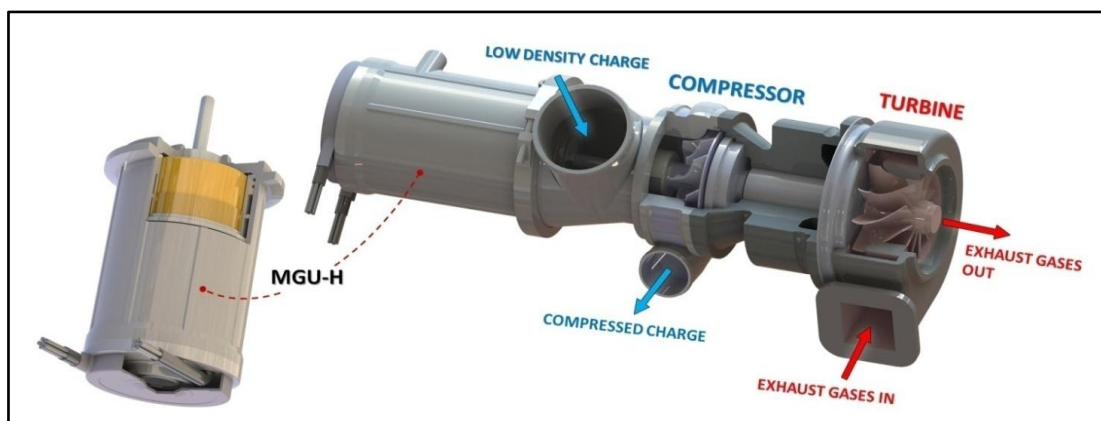


**Fig: 2 V6 turbo engine with MGU-h unit.**

This design flexibility leads to further improvements in turbine and compressor efficiency, beyond a conventional turbocharger. . Fig 2 [5] shows the V6 turbo engine with MGU-H unit.

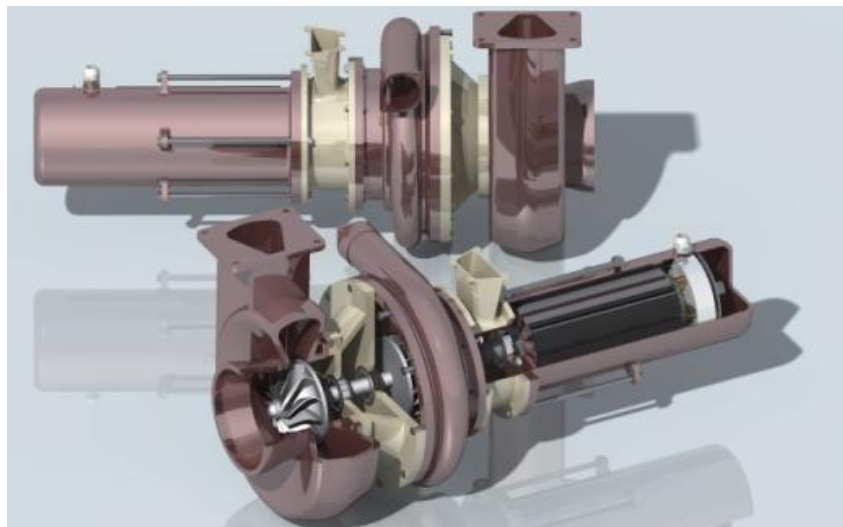
### III. MOTOR GENERATOR UNIT FOR HEAT RECOVERY(MGU-H)

A motor generator unit (MGU) is an electrical machine. When operating as a motor, the MGU converts electrical energy to mechanical energy. When it operates as a generator the MGU converts mechanical energy to electrical energy [6].



**Fig: 3 Assembly of MGU-H assisted turbocharger**

A turbocharger uses an exhaust driven turbine to drive a compressor to increase the density of the intake air consumed by the engine and so make more power for a given displacement. The residual heat energy contained in the exhaust gases after expansion in the cylinders of the engine is converted to mechanical shaft power by the exhaust turbine. The mechanical power from the turbine is used to drive the compressor, and also the MGU-H (H for Heat – exhaust energy recovery) as shown in fig: 3.



**Fig: 4 MGU-H turbocharger design model**

The proposed Motor Generator Unit models for assisting the turbo engine for commercial vehicles is created using design software is shown in fig: 4.

**OPERATION MODES:**

- **Discharging mode:**

When the driver depresses the throttle, the MGU assisted turbocharger initially acts like an electric supercharger. The compressor motor-generator is powered from the energy storage medium allowing it to accelerate to full operating speed in the span of few milliseconds. This rate of acceleration eliminates the turbo lag which is a major limiting factor on the performance of standard turbocharged engines. During this transient stage, the engine control unit (ECU) on a standard turbocharged engine uses a combination of sensors such as lambda sensors and air mass flow sensors to regulate the fuel flow rate. In an MGU assisted equipped turbo-engine the ECU can deliver the precise fuel flow rate for complete combustion more accurately. This is achieved by directly controlling the air flow rate and boost pressure via control of the compressor speed.

Under braking the MGU-H converts to a motor to keep the rotational speed of the turbocharger high enough to avoid turbo lag, the curse of the turbo engine. Turbo lag is a phenomenon experienced under braking when the turbocharger speed slows as a lower volume of gas is produced.

- **Charging mode:** At high engine speeds there is more energy generated by the turbine than is required by the compressor. Under these conditions, the excess energy can be used to recharge the energy storage for the next acceleration phase or used to power some of the electrical loads such as electrical air conditioners, music systems, etc., as shown in tables 2,3&4 .Development is underway for replacing battery energy storage with a super capacitor which can be charged and discharged very quickly.

The proposed MGU-H model is based on these calculations [5, 10]:

$$P_C = \frac{\dot{m}_a}{\eta_c} c_{p_a} T_a (\beta_c^{\lambda_a} - 1) \tag{1}$$

$$P_T = (\dot{m}_a + \dot{m}_f) \eta_T c_{p_e} T_e (1 - \beta_T^{\lambda_e}) \tag{2}$$

$$P_T - P_C + P_{MGU-H} = J\omega \left( \frac{d\omega}{dt} \right) \quad (3)$$

Where,  $\lambda = \left( \frac{k-1}{k} \right)$ ,  $k$  being the isentropic exponent. Through Equations (1) and (2) the power of turbine and compressor are calculated. The dynamic behaviour of the group is known through Equation (3), which includes also the term  $P_{MGU-H}$ , accounting for the power provided (negative) or absorbed (positive) by the MGU-H machine.

Equation (3) can be written in terms of torque:

$$M_T - M_C = J \left( \frac{d\omega}{dt} \right) - M_{MGU-H} \quad (4)$$

Where  $M_T$  is the torque supplied by the turbine,  $M_C$  is the torque required by the compressor;  $J$  is the inertia of the whole group;  $M_{MGU-H}$  is the term accounting for the torque supplied or required by the MGU-H machine.

$$\dot{m}_a = V_t \frac{p_a \beta c}{RT_0} \lambda_v \frac{n}{120} \quad (5)$$

$T_0$  is the intercooler outlet temperature. This equation helps to determine the flow rate aspirated by the ICE in function of the compressor compression ratio for the different operational conditions.

Thus, from the above equations  $P_{MGU-H}$  is the power consumed or power generated from the exhaust gases by harvesting the waste heat with MGU-H assisted turbocharger.

#### IV. RESULTS AND DISCUSSION

The major problem of all turbocharged combustion engines is their delayed response regarding the mean effective pressure build-up at low rpm. The most efficient way to improve the dynamic behaviour of turbocharged engines is to feed the system temporarily with auxiliary power at a certain time.

In the earlier section it was stated that MGU-H assisted turbocharger functions as an electric supercharger to achieve the dynamic behaviour. By considering it the following plots (fig: 5, 6&7) are included.

##### Development objectives:

The development objectives for the MGU-H turbo were defined through performance studies based on the engine simulation.

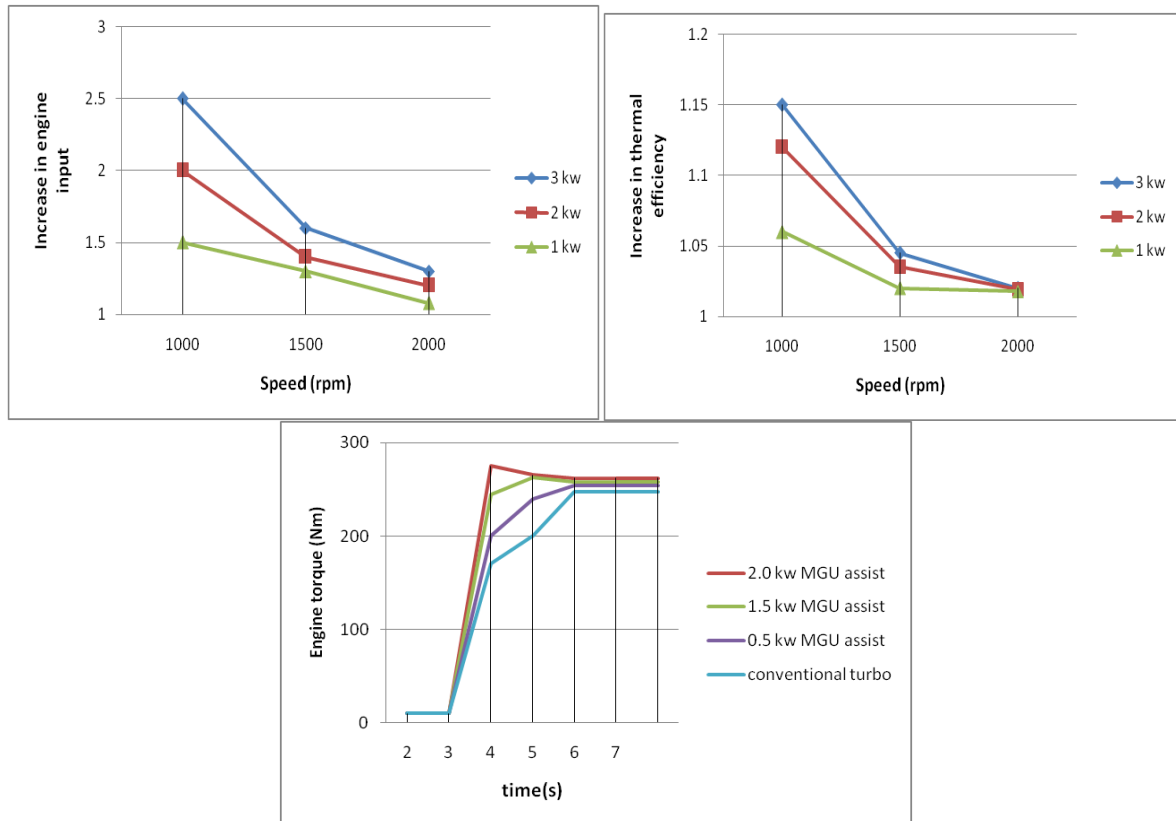
- Improvement of fuel efficiency in the low-engine speed zone
- Improvement of engine torque in the low-engine speed zone
- Reduction of turbo lag during acceleration

The relationship between required motor output and engine performance was estimated in the simulated operation of a 2000 CC engine equipped with an intercooler.

The following data are introduced in the model as parameters:

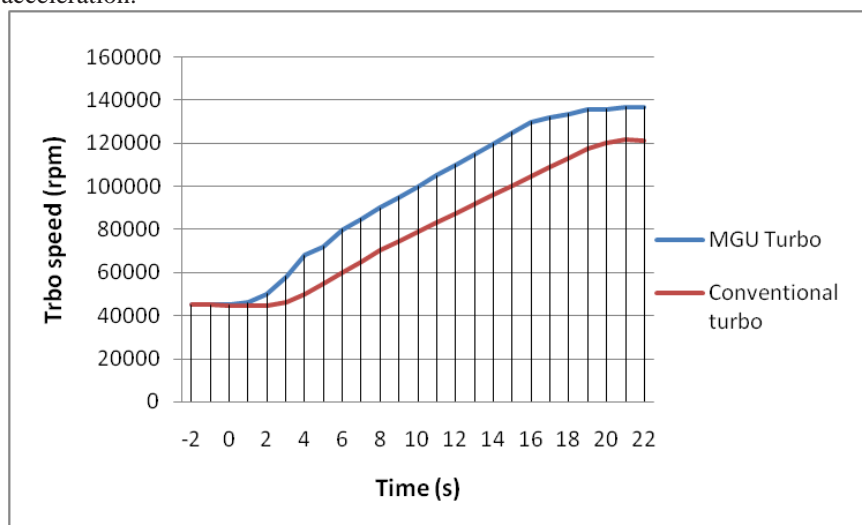
- Inertia of the MGU-H = 0.000112 kg m<sup>2</sup>;
- Inertia of the turbocharger group = 0.00045 kg m<sup>2</sup>;
- Turbine isentropic efficiency = 0.80;
- Compressor isentropic efficiency = 0.72.
- **Fig: 5** shows the performance results. Engine torque as a steady state characteristic was improved by 50 % with a 1 kW motor assist and by 100 % with a 2 kW motor assist. The results also show an 8 % improvement in fuel efficiency with the 1 kW motor assist and a 12 % improvement with 2 kW.





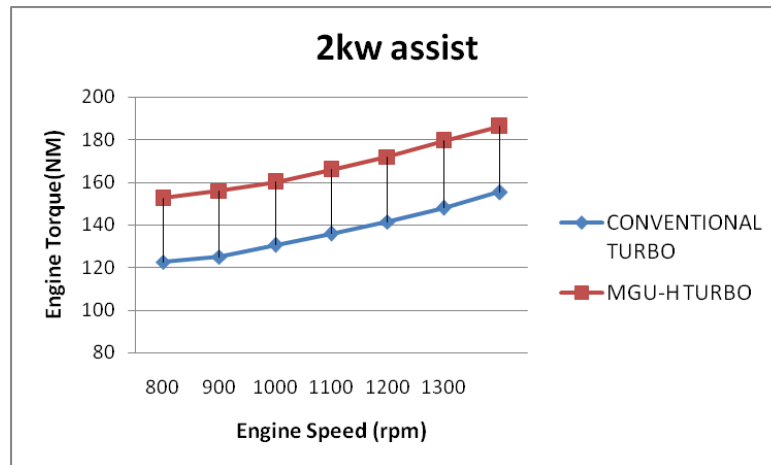
**Fig: 5 Engine performance results**

- Fig: 6** Comparison of the transient response of the turbocharger speed with the MGU assist and without MGU assist. The MGU assistance greatly shortens the start-up times for the turbocharger speed and compressor discharge pressure. The effects of the MGU assist are noticeable if we look at the values during acceleration: the turbocharger took 33 % less time to reach 90,000 rpm. The turbine torque became dominant after several seconds of acceleration.



**Fig: 6 Comparison of the transient response of the turbocharger speed and discharge pressure ratio with the MGU assist and without MGU assist**

- **Fig: 7** compares the steady torque of the engine with the MGU-assisted turbo and with the conventional turbocharger. The steady torque of the engine improved about 17 % at engine speeds of 1000 rpm and 1200 rpm. This effect was mainly due to high density charge supplied to ICE



**Fig: 7 Comparison of the steady torque of the engine between the MGU-H assisted turbo and conventional turbocharger**

#### V. CONCLUSION

So far this technology is being used in formula one racing cars in an effort to reduce fuel consumption. The MGU-H unit used in formula one recovers the waste heat energy and it is stored as an electrical charge adding an additional 2MJ/lap .This technology is not yet adopted for commercial vehicles. Henceforth I hope **“Motor-Generator Unit (MGU) assisted turbocharger for heat energy recovering and improved turbocharging”** technology can also be employed for commercial automotive vehicles to further improve the environmental performance and enhance the pleasure of driving.

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