Study of Energy Recovery Systems in Automobile Industry

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Abstract— This paper discusses the Energy Recovery Systems being used in Formula One and other Hybrid and High Performance Cars, namely Electrical Kinetic Energy Recovery System (KERS) with Exhaust Energy Recovery System, Mechanical ERS and Hydraulic ERS. [4][5]The introduction of Energy Recovery System was primarily to improve Efficiency of cars. [3]But proper exploitation of ERS has not only led to increase of efficiency but has also fulfilled the sudden power demand while overtaking hence reducing lap times[1][2]. The system stores waste energy in a reservoir and releases it under acceleration.

Key words: KERS - Kinetic Energy Recovery System, MGU-K - Motor Generator Unit-Kinetic, MGU-H - Motor Generator Unit-Heat, ES – Energy Storage, ICE – Internal Combustion Engine, CVT – Continuous Variable Transmission

I. INTRODUCTION

A. *Energy Recovery System*

It is a method which utilizes the waste energy leading to minimization of the input energy or increasing the efficiency or output of the device/engine. It is used in many places including furnaces and power plants. But ERS is used widely in Automobile Industry, Particularly in Formula One cars.

The basic concept used in all types of ERS is using the Braking Energy or Exhaust Energy to charge an Energy Reservoir and using the energy accumulated in the Reservoir at a later stage to power the Vehicle. The Energy Recovery Systems are classified based upon the type of Reservoir they use and the method of charging as shown below.

Different types of Energy Recovery Systems being used in the Automobile Industry:

B. *Electrical Kinetic Energy Recovery System (Kers)*

This Energy Recovery System uses the Kinetic Energy while Braking and charges the Reservoir electronically. The Reservoir in KERS is a battery or a Supercapacitor. The Super-capacitors are employed to allow quick charging and discharging using the Braking Energy. The KERS uses Motor Generator Unit-Kinetic which acts as a Generator while charging the Supercapacitor and as a Motor while using the Reservoir energy to power the vehicle.

1) *History*

- 2007- Toyota introduced the Electrical KERS in the Supra HV-R
- 2009- KTM illegally tested Electrical KERS in 125GP in their bike
- 2014- Formula One cars moved from Mechanical KERS to Electrical KERS

C. *Mechanical Energy Recovery System*

This ERS uses Mechanical system instead of an Electronic one. The kinetic brake energy is used to provide rotational energy to a Flywheel which is able to spin at very high RPMs. This Flywheel spinning at high speeds stores a lot of rotational energy which is later directly and mechanically linked back to the wheel to power the vehicle.

1) *History*

- 1950- Transport Buses in Sverdon, Switzerland used Mechanical KERS
- 2002- Honda used Mechanical KERS in their Civic Hybrid
- 2008- Puegeot used Mechanical KERS in their 908-HYBRID for Le Mans
- 2011- Porsche used Mechanical KERS in their 918-RSR

D. *Hydraulic Energy Recovery System*

This ERS uses a pump and pressure accumulator for its operation. The pump is connected to the wheels which while braking pumps the working fluid from a reservoir cylinder to a pressure accumulator. After the pressure increases and the pressure accumulator is highly pressurized, the pressure is released from the accumulator back to the pump which now acts as a Motor and powers the wheel, propelling the vehicle.

1) *History*

- 1999- Hydraulic KERS was used by McLaren Mercedes
- 2007- Hydraulic KERS was developed for US Army vehicles
- 2007- NRG Dynamics used a high efficiency Hydraulic Hybrid System

II. ELECTRICAL KERS AND EXHAUST ENERGY RECOVERY SYSTEM

This Energy Recovery System uses the Kinetic Energy of Braking and charges the Reservoir electronically. The Reservoir in KERS is a battery or a Supercapacitor. The Supercapacitors are employed to allow quick charging and discharging using the Braking Energy. The KERS uses Motor Generator Unit-Kinetic which acts as a Generator while charging the Supercapacitor and as a Motor while using the Reservoir energy to power the vehicle.

A. *Components*

1) *MGU-K*

Motor Generator Unit-Kinetic is the single unit having both the Motor-Generator rotor coils wound on a single rotor. It is used both to charge the batteries while braking and provide additional power when required. It is connected directly to the engine or ICE.

2) MGU-H

Motor Generator Unit- Heat works in much the same way as the MGU-K. However, it is connected to the turbine shaft of the turbocharger, instead of directly to the ICE.

3) Energy Storage Unit (Battery)

High Voltage Lithium Ion batteries are used to both store and deliver energy quickly. Flywheels may also be used in mechanical KERS but F1 uses Supercapacitors as specified by FIA because charging and discharging of conventional batteries in such a short time is not possible.

4) Power Control Unit

It has two functions, first to invert & control the switch of current from battery to the MGUs and second to check the status of the individual cells.

B. Working

The Primary work of MGU-K is charging the Energy Storage to be used as and when required. During acceleration, the MGU-K draws stored energy from the battery system to turn the crankshaft of the ICE at a peak of 120 kW, at an overall lap maximum of 4 MJ output. During deceleration the MGU-K is coupled with the wheel acting as generator to store the Energy from Braking into the batteries.

The MGU-H is responsible for another function other than charging the battery. As MGU-H is connected to the Turbocharger shaft, it can reduce Turbo Lag which occurs at lower engine RPM. Turbo Lag is the inability of the Turbocharger to rotate due to low exhaust speed. The MGU-H uses the energy to rotate the Turbocharger at lower RPM to prevent Turbo lag. Unlike the MGU-K which is limited to recover only up to 2MJ of energy per lap, the MGU-H faces no such limit, it can extract unlimited amount of energy from the Turbo.

1) Before The Starting Of Race

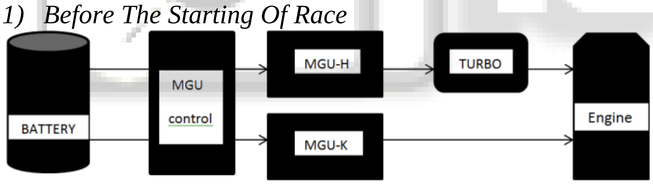

Fig. 1: Race is Starting

When the light is about to go green, the Energy Storage Unit (Battery) is fully charged. All the energy from Energy storage is provided to MGU-H. The MGU-H acts as a MOTOR and speeds up the Turbocharger to reduce Turbo lag. The turbo provides extra compressed air to the engine which increases the power at lower RPMs also.

2) When The Race Starts

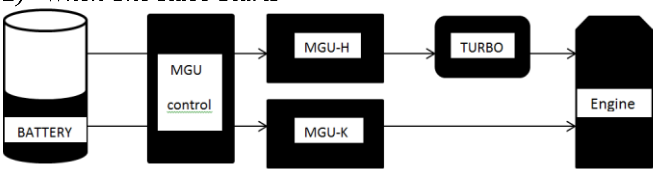

Fig. 2: Race Started

As the Race starts and the cars start to accelerate at part throttle, both the MGU-K and MGU-H acts as MOTORS, discharging the battery. The MGU-K provides acceleration(Boost) to the wheels and MGU-H spools up the Turbo to its Peak. Both work simultaneously to provide maximum power during acceleration.

3) When The Car Is At High Speed

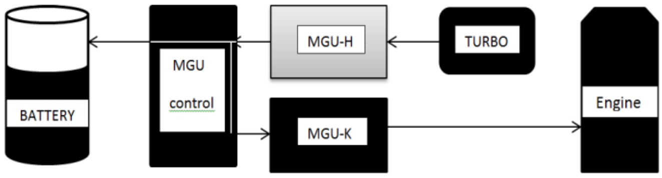

Fig. 3: At High Speed

When the car is at high speed the Turbocharger is using only exhaust gases for functioning, The MGU-H acts as GENERATOR at this time and stores the excess turbine energy in the Energy Storage Unit and charges the Battery. The MGU-K is still acting as MOTOR and using the excess energy from MGU-H and Battery.

4) When The Car Is Braking

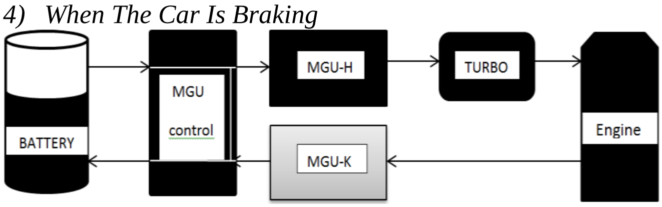

Fig. 4: Braking

When the car is braking, the MGU-K acts as GENERATOR and charges the Energy Storage. Excess power from the MGU-K is sent to the MGU-H acting as MOTOR to spool up the Turbocharger so as to use the Turbo and provide acceleration when required.

C. Advantages of Electrical Kers Used In Formula One

- Reduced CO2 Emissions/Pollutants
- Enhanced Performance
- High power capability, 160 HP extra is obtained from KERS for about 15 seconds.
- Almost No Turbo Lag
- Light weight and small size with Long system life
- Completely Safe and a Truly Green Solution
- A comparison of F1 V8 engines vs. V6 turbo with MGU-H below shows the reduction in Turbo lag at lower RPMs.

D. Limitations Of Electrical Kers Used In Formula One

- The input and output Power of KERS is limited to 60KW.
- The energy recovery system is active only while the car is moving or the engine is running.
- If the KERS is connected between the differential gearbox and the wheels, the torque applied in both the wheels must be equal.
- It is very costly as it uses Super Capacitors. Research is going on to make it more cost effective.

E. Study Of A Formula One Car Using Electrical Kers

The 2016 Formula One Car has the following technical specifications:

- Engine Capacity: 1600CC (1.6 L)
- Engine Configuration: V6
- Minimum Engine weight: 95 KG
- Engine Material: Forged Aluminum Alloy
- Maximum Engine RPM: 15,000
- Maximum Power: 545kW/750HP
- Maximum Power from KERS: 160kW

- Maximum rotational speed of MGU-K: 50,000 RPM
- Maximum torque of MGU-K: 200Nm
- Maximum rotational speed of MGU-H: 125,000 RPM
- Maximum energy transfer from ES to MGU-K allowed per lap: 4MJ
- Maximum energy transfer from MGU-K to ES allowed per lap: 2MJ
- MGU-H can extract unlimited amount of energy per lap

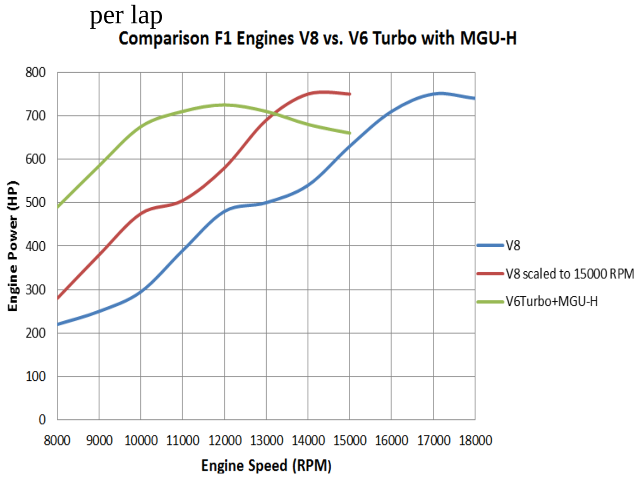

Fig. 5: Engine Power (HP) vs. Engine Speed (RPM) of F1 cars with and without MGU-H

F. Comparison of F1 Cars With And Without Kers

CATEGORY	F1 car without KERS	F1 car with KERS
1. Power of ICE	720 HP	600 HP
2. Total Power	720 HP	760 HP (160 HP KERS)
3. Maximum Torque	4150 Nm	5095 Nm
4. Rev Limit	18,000 RPM	15,000 RPM
5. Acceleration 0-100 Km/hr 0-200 Km/hr 0-300 Km/hr	 1.2 secs 2.6 secs 11 secs	 1.05 secs 2.2 secs 8.0 secs
6. Maximum acceleration force	1.85g	2.28g

Table 1:

III. Mechanical KERS: Flybrid

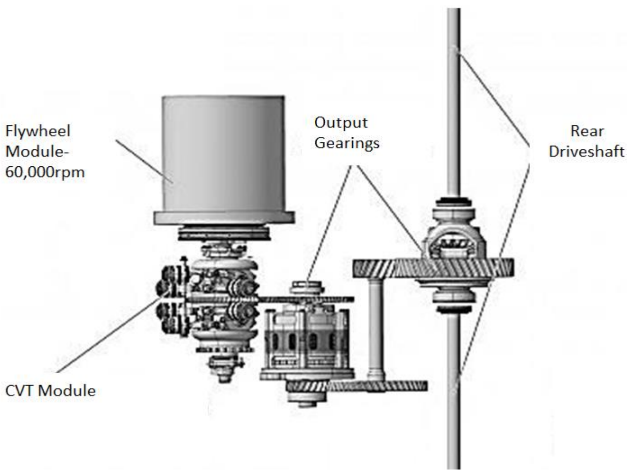

Fig. 6: Mechanical KERS

Mechanical KERS or Flywheel KERS(Flybrid) uses a Flywheel instead of a Battery to store the energy from MGU. The Flywheel is capable of speeds upto 60,000 RPM. The Flywheel is connected using Ceramic bearings which account to minimum Rotational losses.

The flywheel is connected to the transmission of the car on the output side of the transmission through fixed velocity ratios, clutch and a CVT (Continuously Variable Transmission). CVT uses two or more variable diameter Pulleys or Drums or Drives which gradually changes the Gear ratio between the Input and Output shafts without the requirement of finite number of gears. It is a belt driven technology and allows the input shaft to have a constant angular velocity while the output shaft's angular velocity is variable depending on the load.

A. Working

When the car is at high speed and brakes are applied, the driveshaft is coupled to the Flywheel which starts rotating and gradually building speeds upto 60,000 RPM. The Flywheel is made of steel and carbon fibre that rotates inside an evacuated chamber and casing to avoid the escape of any debris. When the power is required, the Flywheel rotating at high speeds is coupled with the wheels and it produces acceleration for about 6 to 7 seconds depending on the speed of the Flywheel and Car. Direct translational kinetic energy to rotational kinetic energy transition and vice versa takes place.

B. Technical Aspects Of Flybrid Technology

- Flywheel now can spin as high as 60,000 RPM 400kJ usable energy storage for 60kW power transmission.
- About 63% of Kinetic Energy is recoverable under braking using Flywheel.
- About 84% of stored energy in the Flywheel is released back to the wheels.
- 80 BHP developed for 6.67 seconds per lap reducing the circuit time by 3 – 4 seconds, which can used all times or as and when required.
- The total system weighs 25kg

C. Mechanical Kers Being Used In Porsche 918 Rsr

Porsche is using a flywheel KERS in its 918 RSR which has a V8 engine and produces 563 HP at 10,300 RPM. The KERS unit adds an additional 204 HP to the engine output taking the total power to 767 HP. The flywheel operates in a Vacuum chamber on ceramic bearings to avoid air resistance which could slow it down. It is capable of speeds up to 36,000 RPM. The energy from flywheel can be used to boost the car for up to 8 seconds. Porsche also claims that their battery pack alone could propel the car up to 16 miles.

D. Advantages Of Mechanical Kers Over Electrical Kers

Super Capacitor based electric hybrid systems require many energy conversions and they have their corresponding losses. On reaching of the energy to the drivetrain, the energy transformation efficiency is about 30%. The Flybrid system storing energy mechanically in a fly wheel discards the various energy conversions and provides energy transformation efficiency greater than 70%, which is more than double the efficiency of an electrical system.

Lithium-ion batteries take 1-2 hours to charge completely due to low specific power hence they are not good for Formula1, so F1 cars use Super Capacitor which can charge and discharge very quickly.

Chemical batteries heat up during charging process and could cause the batteries to lose energy over the cycle or worse even explode.

IV. Hydraulic Energy Recovery System

In Hydraulic ERS regenerative braking energy is used to accumulate hydraulic pressure accumulator which is sent to the wheels via Motor while accelerating. It can capture and reuse around 70% of the vehicle's braking energy.

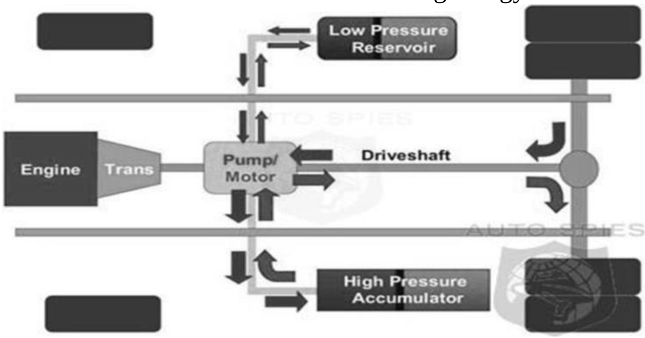

Fig. 7: Hydraulic KERS

A. *Components Of Hydraulic Ers*

- The Working Fluid
- Low Pressure Reservoir
- High Pressure Accumulator
- Pump or Motor

B. *Working*

While braking the kinetic energy of the car is used to charge the hydraulic accumulator through a Pump connected to the wheels. Hydraulic regenerative system uses hydraulic accumulator for storing energy. In hydraulic hybrid system, the pump uses the kinetic energy of braking to pump the working fluid from the reservoir cylinder to the accumulator cylinder. Working fluid is therefore highly pressurized. When the vehicle accelerates, the working fluid from the pressurized cylinder flows back to the motor and provides energy to the motor to propel the vehicle.

There are 2 types of configurations in Vehicles using Hydraulic ERS, Parallel and Series Hydraulic systems.

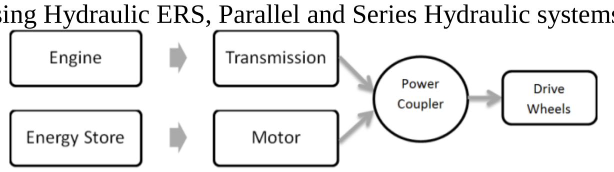

Fig. 8: Parallel Hydraulic System

In parallel hydraulic hybrid system, the pump-motor is installed between the engine and gearbox or the gearbox and transmission box. The function of pump-motor is providing extra power to the engine during acceleration and accumulating energy while braking that would be lost as heat in the non-regenerative brakes. In electric hybrids, the pump-motor may or may not be able to drive the vehicle alone with the engine turned off.

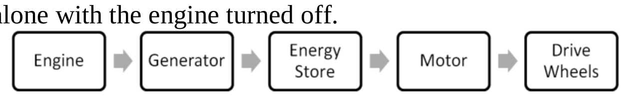

Fig. 9: Series Hydraulic System

In a series hydraulic hybrid system, the pump-motor is directly connected to the driveshaft or the wheel motors providing driving torque directly to the wheel. Only the IC engine is connected to the pump, and is set to operate in the most efficient range to ensure optimal hydraulic pressure in the hydraulic accumulator. The motor must supply whole of the torque required to accelerate the vehicle, thus maximum acceleration is available when the engine is running.

C. *Technical Aspects And Advantages Of Hydraulic Ers Being Used*

- Upto 30% improvement in fuel economy.
- 30% reduction in CO_2 emissions.
- Hydrocarbons and particulate matter production is reduced by 50% and 60% respectively
- Hydraulic hybrids can recover around 70% of the vehicle's kinetic energy
- Brake life is extended by 2-3 times
- In the Estimation of Price calculated for a test vehicle, the hybrid technology added a cost of about $7,000 over a comparable normal vehicle, while the fuel savings for 20 years run were estimated to be above $50,000

D. *Application And Scope*

- Conceptual/Passenger car – minor
- McLaren Mercedes used it on 1999
- City Bus/Delivery Trucks/Garbage Trucks
- EATON-UPS HLA project: up to 35% improved fuel economyand up to 30% CO2 emissions reduction
- Bosch Rexroth HRB for garbage trucks in Germany and US, 20-25% fuel save and 2-3 times brake life extended.
- Technical challenges with hydraulic hybrid vehicles include noise, size, and complexity.

V. Comparison of the Three Technologies

A. *Cost And Material*

Cost is the prime shortcoming of every Hybrid vehicle. Cause of high cost is the material used in making these vehicles and their energy storage technology. Figure shows that flywheel KERS is the cheapest. Flywheels are currently used because of their high efficiency at such a low cost. Batteries are unable to store enough energy as they charge and discharge very quickly. Supercapacitors are the most expensive of them all followed by Hydraulic system followed by Flywheel.

Electric Kers-Super Capacitor	Mechanical Kers-Flywheel	Hydraulic Kers-Hydraulic System
Material - Graphene	Material-Steel,Titanium, Carbon Fiber	Material-Steel,Carbon Fiber
Cost($/Kw) $3626-$10000	Cost($/Kw) $1950-$2200	Cost($/Kw) $2500-$4300

Table 2:

B. Efficiency

Efficiency can be defined as the amount of energy stored to the amount of energy being utilized for other use. Figure shows that flywheel have maximum efficiency with hydraulic storage devices not being too far from it which is followed by Electrical KERS. Batteries have the least efficiency because their discharge rate is faster as compared to the rate at which they charge.

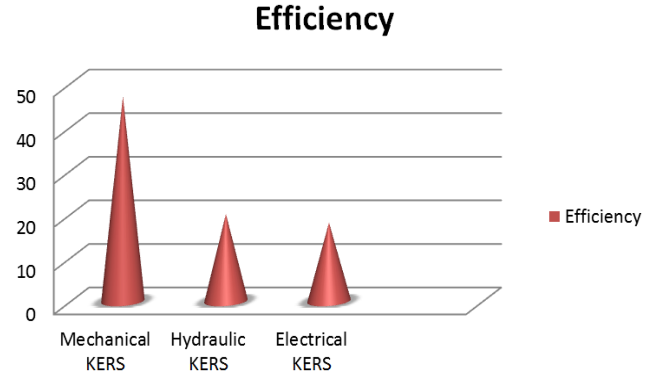

Fig. 10: Efficiency of various KERS

C. Reduction In Fuel Consumption

Reduction in Fuel consumption is the main target of hybrid cars, aiming to conserve and protect the non-renewable sources of energy. 40% of reduction in fuel consumption is found when Supercapacitors are used. Flywheel comes second with 32% reduction in fuel consumption followed by hydraulic energy system which accounts for 30% fuel consumption reduction.

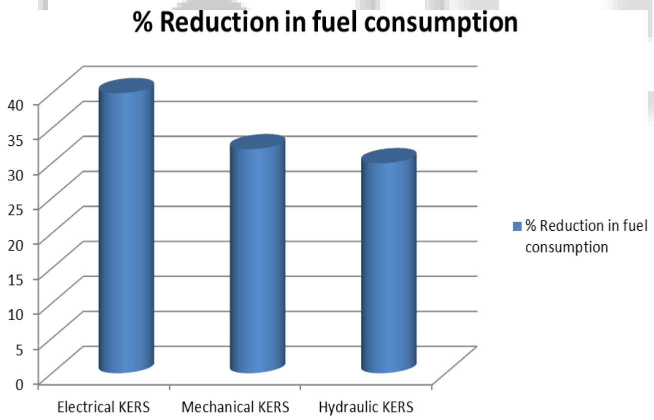

Fig. 11: Reduction in fuel Consumption by KERS

VI. Conclusion

KERS, with whatever technology, is still in the stage of exploration and research. Commercialization of KERS still has a long way to go. KERS is an effective way to improve fuel efficiency by recovering the kinetic energy from braking energy. With the Rising Fuel costs, saving fuel can be very Economical. Use of KERS also benefits environmentally, it reduces waste exhaust gases that cause pollution. Currently, it is mostly widely adopted in the Formula 1 racing. Future application in Aviation, Sailing, Large machinery and Transport is possible which will lead to the best exploitation of this Technology promoting a greener way to travel.

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