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INLINE STARTER GENERATORS (ISG) AND IMPROVED MOTOR COMPONENTS FOR ELECTRIC POWER SUPPLY AND HYBRID DRIVES IN VEHICLES

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ABSTRACT
This paper highlights a range of available Integrated Starter Generator (ISG) and power-electronic controller designs for power generation and hybrid vehicle applications ranging from 35 – 160kW. It addresses the potential for improved integrated system efficiency over traditional alternator-based system solutions.

Robustness of ISG-based systems is evaluated in the paper, particularly when integrated into military vehicles and placed in demanding environments. A range of product realizations is presented, from low-cost solutions intended for higher volume production, to high performance solutions employing state of the art technology. Experience in transitioning from high performance to production-ready realizations is included in support of this evaluation.
ISG generators range up to 160 kW also providing considerable power at idling speed, and crank start capability at low voltage and low temperatures. Their slim design allows for flexible mounting conditions. A family of electronic inverters and converters supplies various output voltage levels at DC and AC phase conditions. The modular approach offers the combination to systems according to various customers' requirements. An integrated device incorporating the low and high voltage DC and AC output in a common box is also available.

The components were developed to meet harsh military requirements. More than 50 systems have successfully completed customer evaluation procedures representing over 350,000 miles of satisfactory operation in TD and EMD phases. This ISG technology is the key for the up-coming high on-board and exportable power demand and provides the transition from mechanical to hybrid propulsion. The ISG in combination with MM's compact and highly efficient electric drive motors gives synergetic hybrid drive systems. They are operated by integrated system control taking into account all electric components, the engine and the mechanical transmission in the various operational areas.

INTRODUCTION

L-3 Communications Magnet-Motor GmbH (MM) and Combat Propulsion Systems (CPS) are well known supplier of highly compact electric propulsion and energy supply systems, in particular for vehicles. This covers prototypes and small series equipment for military vehicles of weight levels up to 28 tons as well as commercial vehicles and passenger cars. An overview of MM's military applications has been presented at previous conferences [1] and [2]. The MM systems include electric motors and generators, power electronics and control and diagnostics elements.

MM has considerable experience supplying prototypes of electric drives and energy supply systems for military and commercial vehicles. Typical examples include the 75kW Integrated Starter Generator (ISG) power generation system for light military vehicle applications (Figure 1), and the Bradley-class 160 kW ISG designed to integrate with the hydromechanical transmission (HMPT) and be fully space claim compliant (Figure 2).

Figure 1: 75kW ISG System for Light Military Vehicle Applications

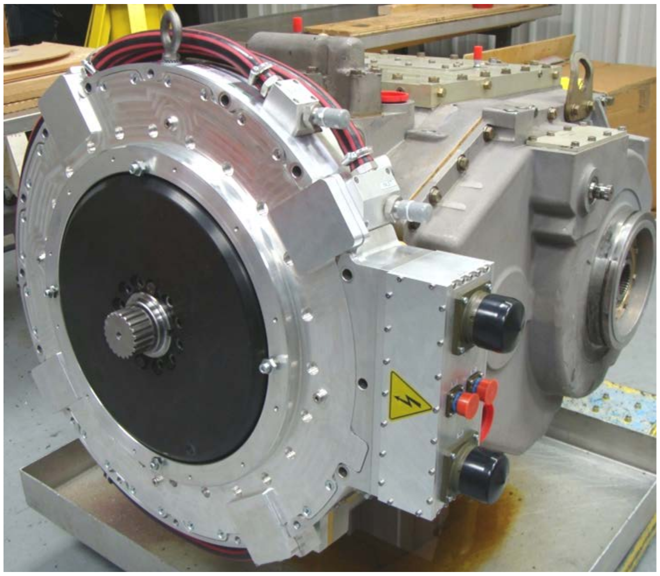

Figure 2: HMPT800EG with 160kW ISG for Bradley-class Military Vehicle Applications

Vehicle systems incorporating ISG's offer best performance at low weight and minimum volume for subsystems under armor and ideal for integration. Integration also means harmonization of control and cooling interfaces. The latter requirement means the connection of the cooling circuits of the vehicle and the electric systems to a common one at the same temperature level in order to avoid double efforts. This approach is hard to fulfill with today's power electronic components that are equipped with Si based IGBT modules and diodes. This technology is being developed for increasing operating current ability but there are technological constraints and physical limits that prevent significant improvements in terms of increased junction temperature of the chips, higher switching frequencies and higher voltage levels with improved efficiency. Silicon Carbide SiC is considered the appropriate way out of these constraints L-3 Magnet-Motor did several development activities that are presented in a separate paper at the EVS24 [3].

Modern military vehicles have a growing demand for more on-board electric power to supply:

- Communication
- Electric air-conditioning
- Controlled air fan
- ECM - Electronic Countermeasures
- Electric suspension ECASS

Additionally, several applications use the vehicles for external power supply. All these requirements have led us to the new product line of Integrated Starter Generators ISG systems. This covers in-line generators which are integrated between the combustion engine and the conventional transmission. Two types have been realized by MM, providing electric power ratings of up to 65 kW @ 2500-4300 rpm (G36) and 75 kW 1900-3000 rpm (G37). For a photograph of the G36 in a demonstration arrangement see Figure 3 below.

Figure 3: G36: 65 kW @ 3500-4300rpm

Other ISG system elements are power electronics elements for processing and supplying the different output options. This includes 24 VDC and 12 VDC and AC 1-phase and 3-phase supply at 120/210 VAC and 220/400 VAC.

THE GENERATOR OF THE ISG SYSTEM

With nearly three decades experience in the design of electric machines Magnet-Motor has developed several different fundamental arrangements. Over the last years the following design principle has been established.

DESIGN

The generators of L-3 Magnet-Motor are designed with a permanent exited inner rotor arrangement. This Rotor is directly coupled with the crankshaft of the engine. For an application with pure electric drive a decoupling device between crankshaft and rotor could be integrated. At the other side if the decision is done to connect rotor and crankshaft direct the rotors mass of inertia can substitute the flywheel of the engine. The interface to the transmission is realized with a flange to the standard flex plate.

The stator of the generator is an intermediate part between engine flywheel housing and transmission housing. The electromagnetic part of this generator is integrated in this housing. The electromagnetic core of the stator is built of laminated sheets with an integrated stainless steel tube for optimized water cooling. The coils of this stator are designed as single coils with additional cooling tubes.

ISG GENERATOR G36

The generator G36 is designed for high speed diesel engines with a nominal speed up to 4300 rpm. One example is the interfaces on the SteyrMotors engine and an Allison 3000 transmission. The rotor substitutes the flywheel and is directly connected to the crankshaft. The interface part between rotor and torque converter is the flex plate with bolts served through the rotor. The cooling water connection feeds through the starter bore. Below are the main data of the G36:

- Power@ 2500 – 4300 rpm: 65 kW
- Weight: 51 kg
- Peak torque: 500 Nm
- Length (between flanges) : 72 mm
- Outer diameter: 452 mm
- SAE #3 flange compatible
- Adaptable to SAE 2
- WEG cooled at 75 °C

Figure 4: Generator G36 mounted at SteyrMotors engine

ISG GENERATOR G37

The generator G37 is designed for medium speed diesel engines with a nominal speed up to 3000 rpm. The engine interface fits to a Cummins engine and to an Allison 3000 transmission. In the prototype arrangement the engine flywheel is not modified and the connection rotor flex plate is realized by an additional radial service bore. Water cooling connection is radial outside the stator. The following overview shows the main data of the G37:

- Power@ 1900 – 3000 rpm: 75 kW
- Weight: 72 kg
- Peak torque: 750 Nm
- Length (between flanges) : 152 mm
- Outer diameter: 452 mm
- SAE #3 flange compatible
- Adaptable to SAE 2
- WEG cooled at 75 °C

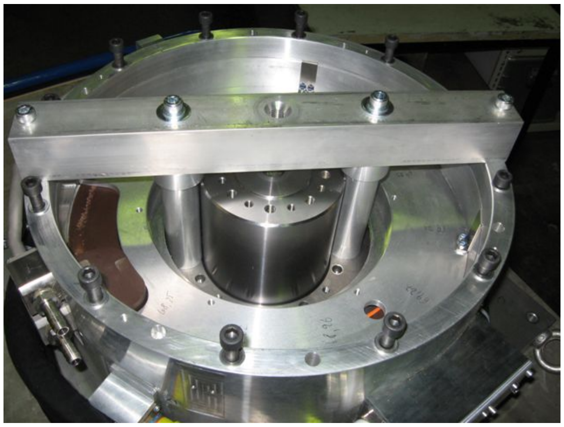

Figure 5: G37Generator

The ISG BACK TO BACK TEST OPERATION

Figure 6 below shows the hardware equipment of the generator G36 in back to back operation.

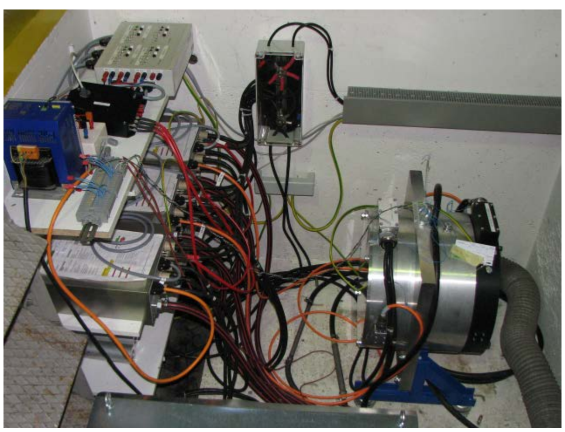

Figure 6: Test stand set-up of two MM generators G36 and three PE31 inverters

In this arrangement the one generator runs as motor to drive the second one running as generator. The advantage of this arrangement is that the common DC-link only needs as power input the losses of this system. In Figure 6 the third PE31 runs as break chopper to stabilize the voltage of this test arrangement.

In the back to back operation four different types of cycles have been tested:

1. Continuous torque 250 Nm @ 600 rpm
2. Thermal cycles 250 Nm @ 600 rpm & 0 Nm
3. Full speed 4300 Nm @ 75 kW
4. Partial load 30 kW speed cycles 1500 to 4300 rpm

Cycle no. 2 is very interesting with the relation to an engine: The tested 182 cycles with 13 min 250 Nm starting torque is equivalent to 47320 cycles with 3s 250 Nm starting torque for engine start, a benefit for engine suppliers.

POWER ELECTRONICS/INVERTERS

The ISG system is designed for multiple configurations. Figure 7 shows an overview of all principal components of this system. The generator mounted between engine and transmission is connected by an AC to DC converter to the backbone of this system to the common DC link. To the common DC link is connected a DC to DC converter that serves as charge converter the vehicle board net. A DC to AC converter connected to the DC link opens the possibility to serve all AC applications. An additional high voltage DC to DC converter allows the integration of a high power drive battery and the conversion of this vehicle to a hybrid vehicle.

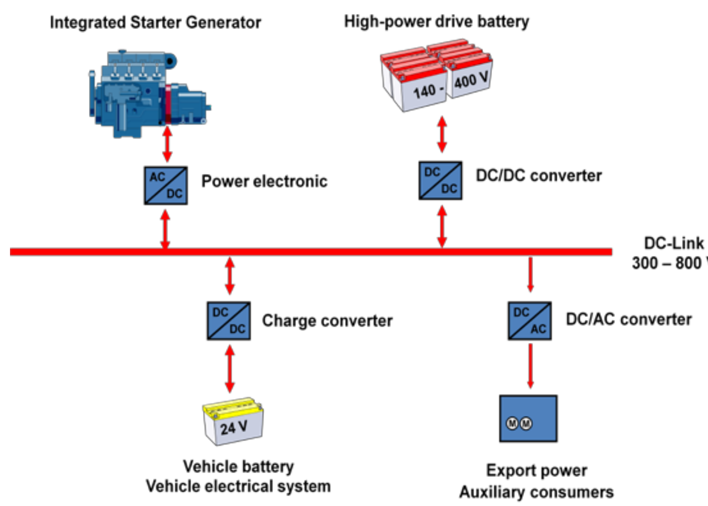

Figure 7: Block diagram of the ISG system

POWER ELECTRONICS - PE31

The power electronics PE31 is a unit suitable for several applications. It was developed as power electronics for a 130 kW generator and a drive motor of a wheel drive unit with 1.5 Ton wheel load. This unit is multi functional. It has performed as an inverter for traction motors, ISGs, and other rotating machines. It has also performed as a brake chopper when large brake resistors are required in mobility applications. It can be used as a single unit (as with M69) or coupled in parallel for larger devices (as with G40). The PE31 is designed as a compact three phase water cooled unit with the following characteristics:

- Switching power: 130 kW (cont.)
- DC voltage: 800 V DC
- Volume: 10.4 dm^3
- Weight: 15.2 kg

Figure 8: The power electronic PE 31

DC to DC CONVERTERS - LW01

The main functionality of the ISG system is the charging of the vehicle board net. The charge converter LW01 allows a multiple parallel operation with a maximum power output at 28 V up to the nominal power of the ISG – system.

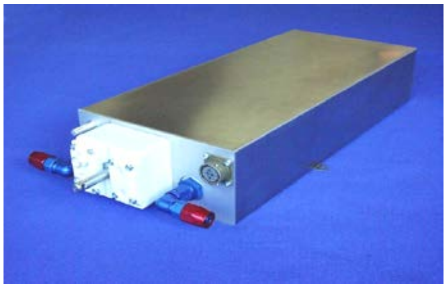

Figure 9: DC to DC converter LW01

The technical data of the LW01 are summarized as the following:

- DC input voltage: 300 – 800 VDC
- DC output voltage: 28 VDC
- Charge power: 5 kW @ 28 VDC
- Volume: 5.9 dm^3
- Weight: 11 kg
- Cooling: WEG

With minor modifications the LW01 is also able to run at 14 V output voltage with 2.5 kW power.

BIDIRECTIONAL DC to DC CONVERTER CHC 02

For vehicle operation, a very important functionality of the ISG – system is the engine start. For an engine start from the 24 V board net at low temperature the voltage drops below 20 V. Together with the voltage step at the IGBT and the induced back EMF of the permanent exited generator an engine start needs a battery network to achieve a voltage higher than 30 V or a charge converter with up converting functionality. Several customers have the requirement of an advanced power demand. Therefore L-3 made a decision to develop a bidirectional charge converter with a higher power output.

These characteristics are:

- DC input voltage: 400 – 800 VDC
- DC output voltage: 28 VDC
- Charge power: 13 kW @ 28 VDC
- Volume: 14 dm^3
- Weight: 19.1 kg
- Cooling: WEG

DC to AC CONVERTER ACC 04

Future vehicles with additional electric functionalities will certainly use more high voltage power supplies to avoid heavy cooper cross sections in the vehicles. To run these high power loads a two or three phase AC subsystem can be a future solution. As compact powerful water cooled unit with internal electric filter the DC to AC converter ACC04 could serve an AC vehicle board net.

Figure 10: DC to AC converter ACC04

This unit can be synchronized with more similar units to build an electric island net or to feed the electric grid.
Having the following characteristics:

- DC input voltage: 300 – 800 VDC
- Rated output voltage: 120/200 VAC
- Cont. output power: 38 kVA
- Volume: approx. 41 dm^3
- Weight: approx. 75 kg

HIGH VOLTAGE DC to DC CONVERTER DCC 06

A high voltage high power DC to DC converter allows integrating a high power battery to the ISG system. The DC to DC converter DCC06 is designed similar to all other L-3 MM power electronic units; compact, robust water cooled units.

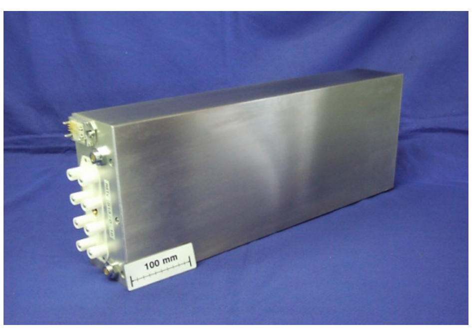

Figure 11: DC to DC converter DCC06

It has the following technical characteristics :

- DC input voltage: 300 – 800 VDC
- DC output voltage: 140 - 400 VDC
- Power: 80 kW (max) / 30 kW (cont.)
- Volume: 18 dm^3
- Weight: 35 kg

VEHICLE HYBRIDISATION

An electric Mild Hybrid system is the combination of a powerful Integrated Starter Generator ISG with a power battery. The ISG is integrated between an internal combustion engine and the mechanical transmission. The mechanical connections can be switched on and off by means of clutches which are arranged between these three elements. The power battery is integrated into the DC part of the ISG system. Figure 11 shows the basic structure of the electrical and mechanical elements.

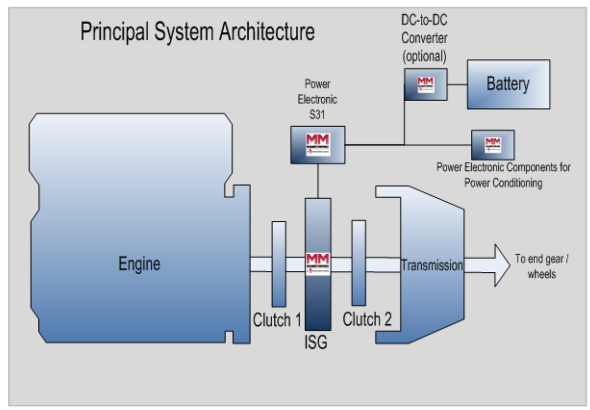

Figure 12: Basic Structure ISG Mild Hybrid

There are at least three different operating conditions:

1. Both clutches are switched on. This is conventional mechanical driveline operation which includes the on-board power supply by the ISG and recharging the battery.

2. Clutch 1 between the internal combustion engine and ISG is switched on; clutch 2 between ISG and transmission is switched off. The engine is operating the generator during vehicle park conditions. The ISG system provides export power, it operates as a mobile power plant.

3. Clutch 1 between combustion engine and ISG is switched off, clutch 2 between ISG and transmission is switched on. This is a full electric drive system with the ISG generator operating as a drive motor and powered by the battery. This configuration can be used for silent watch and stealth mode operation.

Conventional ISG generators are able to provide just the power to feed the on-board electric power systems and to crank start the engine. However such power performance is too little for the Mild Hybrid operation as described above. For realistic contribution to the mechanic propulsion power both the ISG generator in the motor mode and the battery should be more powerful. The MM ISG system is designed to higher power ratings thus enabling the full flexibility of the Mild Hybrid operation.

EXTENDED PROPULSION CAPABILITIES

During acceleration a considerable amount of propulsion power is dissipated in internal and external friction losses e.g. in the bearings of the drive train, in the spinning tires (churning effect), air resistance and other losses. The additional electrical power is a full add-on to the mechanical acceleration power and can be completely added to the driving performance.

This property is illustrated in Figure 13 below. The example is based on a wheeled vehicle of 6.5 tons and a diesel engine with 136 kW of mechanical power. For simplification the shift point operation of the transmission is simulated by an overall effective propulsion power. The two lines show the acceleration performance on flat terrain by using different sources of power. The red line indicates the conventional Diesel engine power train as the sole power source. This is compared to the Mild Hybrid alternative indicated by the blue line with the same engine supported by an electrical ISG arrangement. In this example the additional power of 20 kW is added to the drive train. Thus the power which is available for propulsion purpose increases considerably. Another positive effect is given by the additional torque provided by the generator running in motor mode that is available from zero speed.

The acceleration of the vehicle is significantly higher, it also can reach even higher maximum speed.

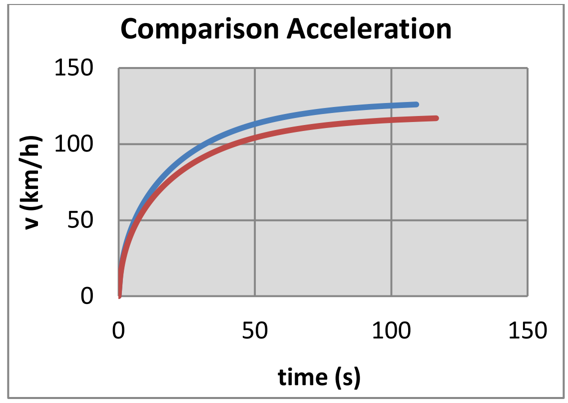

Figure 13: Comparison of acceleration with and without ISG support on flat terrain.

More drastic effect to the acceleration happens during slope operation of the vehicle. The curves in Figure 14 show the results of the same vehicle but just operating in a 10% slope. The reason is that much more power from the diesel engine is needed to operate the vehicle on the slope thus reducing the available power dramatically.

This is highlighting the great benefit of higher mobility and maneuverability of the vehicle in all terrains and driving conditions.

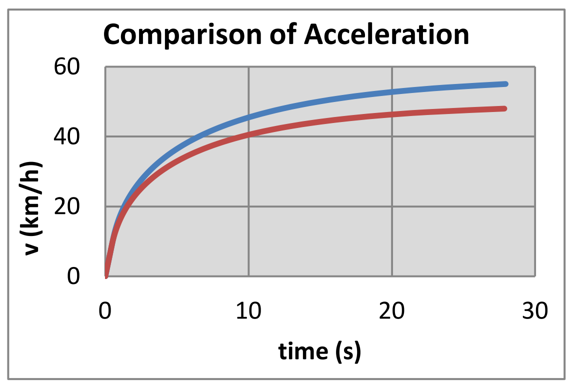

Figure 14: Comparison of acceleration with and without ISG support on road with a 10% incline

The effects on improved mobility in an overview:

- Much better acceleration
- Advanced hill climbing properties
- Accelerated change of position.

SILENT WATCH AND STEALTH MODE

With the prime mover switched-off and disconnected from the drive train, the pure electric propulsion mode of the electrical hybrid offers tactical operations to the vehicle which are not possible with a conventionally driven vehicle:

- Significant extension of surveillance periods by battery powering only, e.g. in external emplacement with running on-board systems but without running the Diesel engine.
- Significant reduction of IR and acoustic signature caused by the possibility of shutting down the Diesel engine.
- The vehicle can operate on battery power only without any noise emissions.
- Jump out of defilade without running Diesel engine.
- Quick start of the Diesel engine supplied by the battery.

MOBILE POWER PLANT

With the transmission disconnected from the Diesel engine/ISG (i.e. alternative 2 above) the vehicle is able to serve as a mobile power plant: The engine only operates the generator, providing electric power to external consumers. Multiple connection of a couple of vehicle enables higher power output.

TRACKED VEHICLE OPERATIONS

The ISG architectures discussed have applications in tracked vehicles as well. G40 (160kW each) 430 HP sandwiched between a 1000 HP engine and 800 HP HMPT transmission has been created for vehicle weighs to 50 tons. Through analysis, two continuous sprocket power curves were produced as shown in Figure 15. The lower curve represents a tradition pure mechanical transmission with and ISG available only to provide 67 HP (50kW) of power to on board electrical loads. The higher curve demonstrates the benefits of E-Motor assist due to the more efficient power path of the electric machines. As shown in Figure 16, electric motors are coupled to the mechanical transmission outputs. When the ISG redirects power around the mechanical transmission to the electrical motors (electrically), the electrical power can be added (or coupled) to the mechanical power created an increased net (or usable) sprocket power.

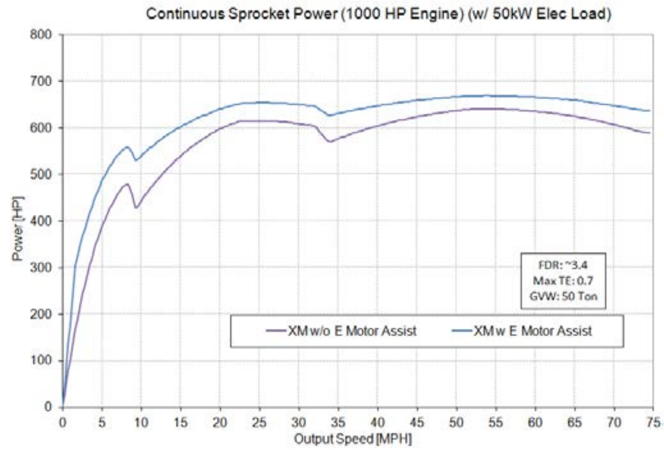

Figure 15: Continuous Sprocket Power

This proof of concept has been demonstrated in a dyno lab at L3 CPS as shown in Figure 16. The HMPT800EG, which consists of a modified HMPT800 and a G40 160KW ISG, was integrated with two M69 traction drive MM motors into a dyno lab. The M69 Motors were directly coupled to vehicle simulation dyno shafts that couple to the transmission output shafts. The Electric Motor assist concept was validated and improvements in transmission efficiencies were measured.

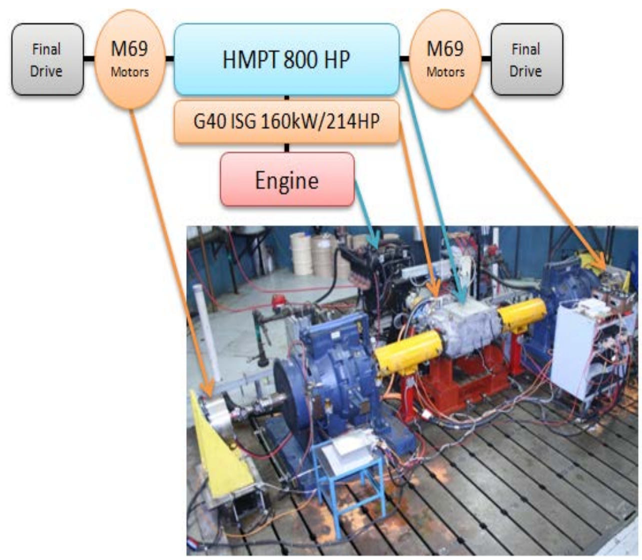

Figure 16: Electric Motor Assist Proof of Concept

The initial results were promising. Figure 17 shows data captured during testing. Engine power and speed was held constant at 450 HP@175 RPM through the test. During the first 78 seconds the output was purely mechanical and output was measured at 200 HP. Between roughly 78-141 seconds the E-motor assist was activated and the output power was measured at 250 HP, while the engine input power remained 450 HP. Because the ISG to electric traction motor power path to the sprocket was so much more efficient at these operating conditions, the sprocket power increased 50 HP.

This data validated the analytical and conceptual with hardware in the loop. It demonstrated that given the proper architecture, having a combined electro-hydro-mechanical transmission will improved performance, and efficiency.

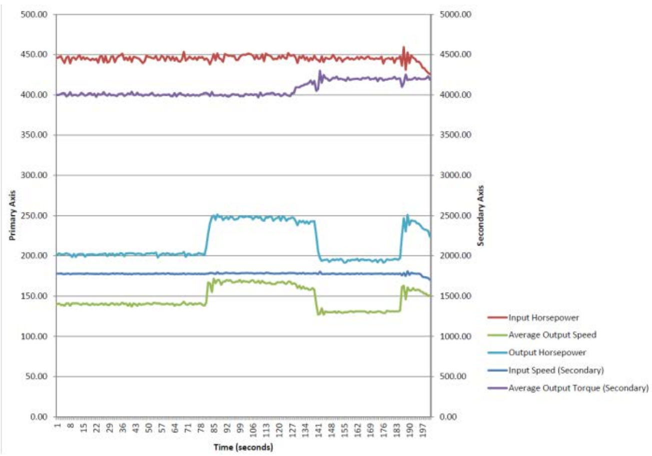

Figure 17: XM Output E-Motor Off-On-Off

Burst Power Mobility

A generic ISG architecture for Tracked Vehicles is shown in Figure 18.

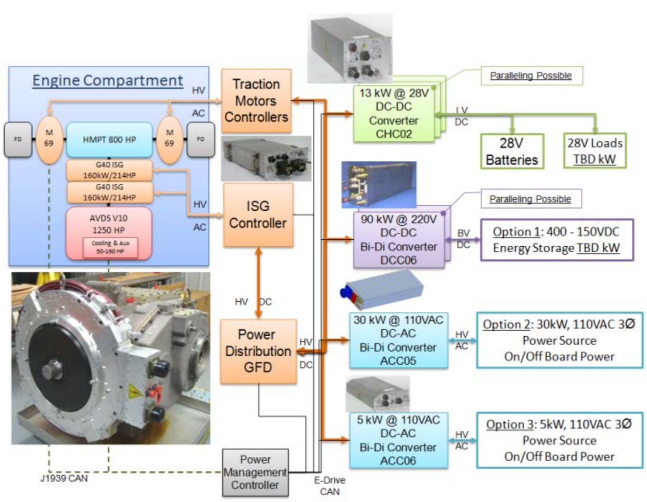

Figure 18: Generic Tracked Vehicle Distributed Architecture

The ISG and Electric Motors providing power for traction will improve vehicle performance whenever immediately available torque from the electrical motors can assist the mobility of the vehicle. Sort transient events, such as obstacle crossing, steering, braking, and acceleration, will benefit from these electric transmission components. Figure 19 shows how well propulsion batteries improve acceleration with less than a quarter of equivalent engine rated power added to the architecture.

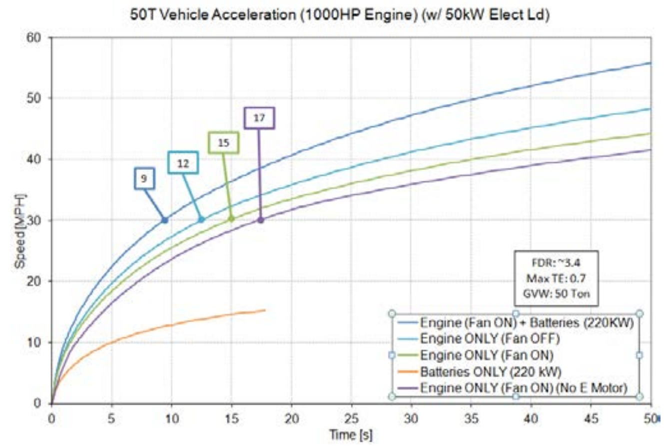

Figure 19: Acceleration Comparisons

ADDITIONAL ADVANTAGES AND OPTIONS

- Reduction of fuel consumption:
  Experiences from local traffic applications show a reduction in fuel consumption of up to 20-25%. Simulations and relevant test stand measurements may prove a representative value for military vehicles as well.
- Silent running mode with reduced power.
- The electric enhancement offers faster speeding of the Diesel engine to its maximum rpm speed supported by the ISG. The maximum Diesel power can be reached in a much shorter time period: This offers a considerable improvement of the vehicle survival capability.
- Easier fording and crossing of water due to switch-off of the Diesel engine.
- Emergency drive mode in the case of a Diesel engine brake down. The electrical technology allows the disconnection of a broken down Diesel engine and a completely electrical drive mode.

The advantages and properties mentioned in this article are all individual aspects. Furthermore, one of the most important arguments of the electric propulsion technology is that all mentioned functions run harmonized. The decisive role in this context plays the electronic energy and power management which connects all components and leads to a synergetic function of the whole system. This offers optimal functions of the system using harmonized control algorithms and feedback.

All the possibilities of an ISG – system integrated to a vehicle lead to the conclusion, the ISG is important for the transition from traditional to 21st Century configurations for wheeled and tracked military ground vehicles.

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