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Preliminary design of a hybrid electric powertrain for a earthmoving machine

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Abstract

The goal of this work is to evaluate the benefit of the hybridization of a Compact Wheel Loader (CWL) and to put into evidence the effect of the component size on its performance. To do this, a mathematical model has been developed using a backward approach, i.e. starting from the power request on a typical duty cycle made available by an industrial partner. The goals for the choice of the hybridization architecture were: minimizing fuel consumption, ensuring the simplicity of driveline and power management and ensuring compatibility with the vehicle structure.. A reduction up to 14% of fuel consumption was estimated in this investigation by combining engine downsizing with the usage of a Continuous Variable Transmission together with an optimization of the battery capacity and voltage.

Keywords: compact wheel loader, hybrid electric power systems, series/parallel configuration, parametric analysis

Introduction

Research on hybrid electric power systems (i.e. systems equipped with at least two different kinds of energy storage systems/ converters) has started in the automotive field but is becoming more and more relevant in other

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applications, including heady duty machines, ships and aircraft because of the potential of reducing fuel consumption and environmental impact. In this direction, some hybrid earthmoving machines were proposed in literature and some of them were actually introduced on the market, offering a valid alternative to conventional systems. Differently from aircraft and automotive applications, the increased mass of these advanced systems (mainly due to the secondary storage system) is not a problem in the case of earth-moving machines because it can be compensated by a decrease of the counterweight.

Different kind of secondary storage systems for hybrid earthmoving machines are presented in [1]: batteries, supercapacitors, hydraulic accumulators or flywheels. However, batteries are the common choice being the best compromise between power density and energy density. Two fundamental architectures can be used in hybrid systems ([2]). In a series architecture, the internal combustion engine (ICE) is connected to the final transmission through two electric machines. The engine mechanical output is first converted into electric energy (with a generator) and then again into mechanical energy by a motor. The motor receives a current that is the algebraic sum of the generator output and the battery current. This configuration makes easier for the engine to work at fixed point and therefore, at its best efficiency. On the other hand, the overall efficiency is penalized by the double power conversion in the two electric machines. In a parallel configuration, the mechanical propulsion energy is delivered by the electric motor and the ICE in two parallel paths. Usually, the ICE is the basic propulsion unit, while the electric machine is used, as a motor, when power request is higher than the engine rated power or, as a generator, to charge the battery. Other hybrid architectures can be realized taking advantage from both series and parallel configurations at the expenses of greater complexity and installation costs.

In this study, the target of the hybridization was not only minimizing fuel consumption, but also ensuring the simplicity of driveline and power management with respect to the conventional system of a Compact Wheel Loader (CWL). As a result, a hybrid electric architecture composed by a parallel configuration for the pump and a series configuration for wheels driveline, similar to that proposed in [3], is considered. A sensitivity analysis of the main components of the power systems is performed in this work to analyze the effect of engine size and battery specification in terms of voltage and capacity on the fuel consumption. To evaluate fuel consumption, a backward approach like in [4] ls used, starting from acquired data during a test for a typical duty cycle. In particular, the requested power from boom/bucket pump and the CWL speed measured during an experimental test are used to size and analyze the hybrid electric system. For this reason, a model of the hydraulic circuit is required in this work.

Another key issue in the development of hybrid electric power system is the energy management strategy. In literature, several energy management strategies were proposed [5],[6],[7]. Optimal energy management strategies can be based on offline optimization (but the drive cycle must be known a priori), or on an online analysis, where controller makes decisions during the cycle. The "heuristic" map-based and rule-based approaches are the simplest ones and, for this reason, were preferred in this work. The engine working point is kept constant during the duty cycle and the energy management is performed by using the battery to match the variable power request.

1. Hybrid electric earthmoving machines

The preliminary analysis of the state of the art about hybrid electric earthmoving machines has been the first step to understand which possibilities could be taken in account to develop the model of the hybrid electric CWL.

The Komatsu HB215LC-2 Hybrid excavator has a swing motor/generator that recovers energy during upper structure deceleration, converting it in electric energy: recovered energy is delivered by supercapacitor during accelerations, helping ICE and reducing fuel consumption [8]. In the Kobelco SK210HLC-10 Hybrid excavator, the swing motor is feed by the electric energy stored in Li-Ion battery. During high load operations, the motor/generator gives to the ICE a supply power of about 25 kW and during upper-structure deceleration energy is recovered into the battery. [9]. Volvo developed two hybrid electric wheel loaders: the first one is the L220F Hybrid, which took origin from an existent model [10], and the second is the LX1, which is a completely redesigned prototype to reduce significantly fuel consumption and optimize machine size [11].

John Deere[12], with models 644K Hybrid and 944K Hybrid, covered two levels of power with an hybrid system that permits the ICE to run at a fixed number of rpm, avoiding sudden changes of work conditions that can increase fuel consumption- Kramer 5055e is a full electric Compact Wheel Loader, which delivers a traction power for wheels of 15 kW and a hydraulic power for pumps of 22 kW: obviously, this is a plug-in system, that takes electric energy from the grid, and has a high-sized batteries pack, which has a 80V voltage, a 416 Ah capacity and a total mass of 1230 kg [13]. Merlo TF 40.7 Hybrid is a telehandler provided by a downsized ICE, from 90 kW to 56 kW, covering the rest of the power by electric advices. It permits to work into closed environment with very low noise levels [14].

A summary of the systems proposed in literature is reported in Table 1.

Table 1.Hybrid electric earthmoving machines

An example of a column heading	Typology	Declared reduction of fuel consumption	References
Komatsu HB215LC-2 Hybrid	Excavator	20%	[8]
Kobelco Hybrid SK210HLC-10	Excavator	12,3%	[9]
Volvo L220F Hybrid	Wheel Loader	10%	[10]
Volvo LX1	Wheel Loader	35%	[11]
John Deere 644K/944K Hybrid	Wheel Loader	25%	[12]
Kramer 5055e (full electric)	Compact Wheel Loader	(full electric)	[13]
Merlo TF 40.7 Hybrid	Telehandler	30%	[14]

2. The conventional Compact Wheel Loader

Details about the performance of the conventional CWL used as starting point for the hybridization cannot be reported here because of a confidentiality agreement. Experimental data available for this vehicle were used to derive the power request during a typical duty cycle and to validate the simulation approach.

3.1. Duty cycle

The chosen CWL duty cycle is the standard Y duty cycle, which takes his name from the Y-shaped path followed in the horizontal plane by loaders in their usual employment. In the first half of the duty cycle, the vehicle is unloaded and moves forward to reach the point for the bucket filling. In the filling phase, the loader moves forward at a very low speed. When the bucket is loaded, the vehicle can move backward, returning to the initial point. Then it goes forward to the point where it has to empty the bucket. Finally, the unloaded vehicle moves backwards returning back to its initial position [15]. In Fig.1the speed profile is reported in absolute value, and is possible to recognize the different phases of duty cycle. Each cycle lasts about 70s but, to size the battery, the cycle was repeated 50 times (corresponding to about 1 hour of operation).

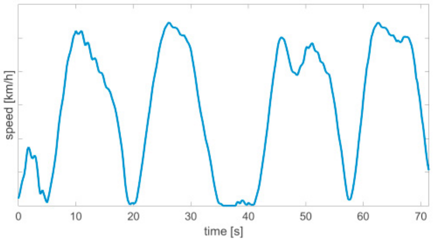
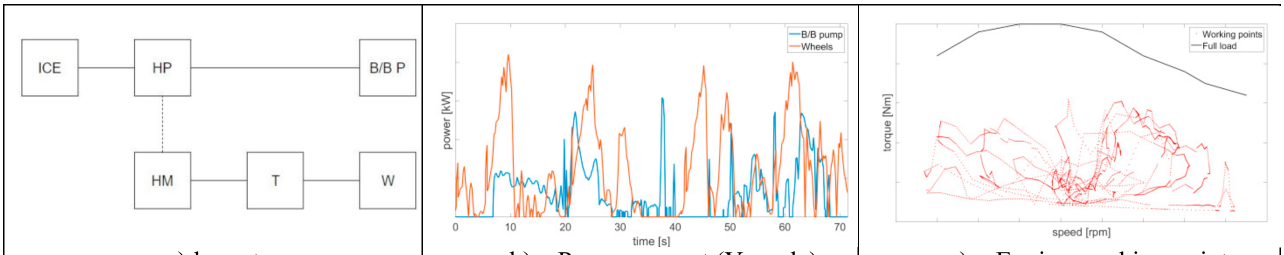


Fig.1. Speed of Compact Wheel Loader (absolute value) during a Y-cycle

3.2. Modeling approach and validation

In the present hydrostatic configuration of the CWL, the gas pedal controls the engine speed, while lift and tilt levers control the valves in the hydraulics system that ultimately control the movements of the linkage's lift and tilt cylinders, respectively [16]. The powertrain consists of a diesel engine (ICE) that moves, on the same shaft, both the boom/bucket pump (B/B P) and the hydrostatic pump (HP), which is connected through an hydrostatic transmission to an hydrostatic motor (HM). This allows mechanical energy to be transferred to the transmission (T) and then to the wheels (W), as represented in Fig.2a.



a) layout b) Power request (Y-cycle) c) Engine working points

Fig.2. Present architecture of the Compact Wheel Loader

The backward approach is usually in the analysis of the performances of hybrid electric systems while the forward approach, which simulates the control on the gas pedal and joystick to match the required speed profile, is required for the actual implementation of the energy management strategies.

In the backward modeling approach used in this paper, the power request of HP and HM along the duty cycle (Fig.2b) is used to enter the efficiency map of the internal combustion engine (furnished by the industrial partner) and to evaluate the overall fuel consumption. In this way, it was not necessary to model the other components of the powertrain. The overall fuel consumption obtained with the simulation was sufficiently accurate (being only 0.8% higher than the experimental data acquired by the industrial partner over the same cycle). The engine currently used in the CWL is oversized with respect to the total power request on the Y-cycle by about 40% (and therefore the engine working points are well below the maximum torque curve as shown in Fig.2c). This comes not only from the necessity of guaranteeing excess power for more demanding maneuvers but also from the choice of using the same engine on different earthmoving machines for money saving reasons.

3. Proposed Hybrid Electric architecture

In the original power system, the engine is run at the same speed of the B/B pump which is an input of the model. In fact, its time history in the Y-cycle is obtained from the experimental data together with the required power. The goal of the proposed hybrid architecture was to run the engine at constant speed and load, and to use a battery as energy buffer. In a typical parallel configuration, this is not possible because the engine speed is influenced by the rest of the elements coupled by sprockets. From this point of view, a series configuration would be more suitable despite the bigger size and mass of electrical machines.

The proposed hybridization scheme (see Fig.3) tries to take advantage of both series and parallel configurations. It consists of an electric machine EM1 and an ICE with a Continuously Variable Transmission (CVT), coupled in parallel with the boom/bucket pump by a torque coupler. A series connection is used to move the wheels driveline which is based on four electric motors, generically represented in Fig.3 as EM2. The electric motors receive a current which is the algebraic sum of the electric output/input of EM1 and the current to/from the battery which can be recharged by regenerative braking and by the generator, when pump power request is lower than power provided by the ICE. In the scheme of Fig.3, single continuous lines are used to represent mechanical connection while a double continuous line is used for the electrical buses. Each electric machine needs an inverter that is not represented in the figure for simplicity. This configuration is not new in literature. In fact is has been proposed by Merlo telehandler, as described in [3] and is based on a CVT (Continuous Variable Transmission) to run the ICE at fixed point, while meeting the torque request with a varying transmission rate as described in [17]. A CVT consists of a metal belt (or a chain) and two V-shaped pulleys. Each of the pulleys is connected to a hydraulic actuation system that allows the selected transmission ratio to be obtained. One of the output of the design procedure is also the minimum and maximum transmission ratio of the CVT to allow the engine to run at constant speed while the EM1 follows the B/B pump speed dynamics.

As for the components, two different size of the engines were considered: the original one and a scaled engine with a reduced power (-55% of the original engine). The EM2 was sized according to the maximum power request of the wheels, while EM1 was size according to both the power request of the pump and the specification of the battery.

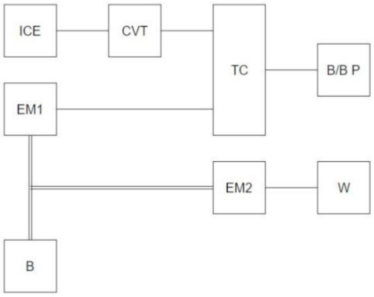


Fig.3. Compact Wheel Loader hybrid electric configuration

The energy stored in the battery depends on its nominal values of capacity and voltage while the usable energy depends on the depth of discharge allowed for the battery. The electrical power that the battery can generate depends on its voltage and nominal C_{rate}, i.e. on the maximum discharge current expressed as a multiple of its capacity in Ah [18].A parametric study on the nominal specification of the battery has been performed in the present investigation taking into account commercial Lithium-polymer batteries [18]. Lithium-polymer cells are preferred in transportation for their higher energy density and their flexibility of shaping. However, they are prone to explosions if not correctly managed. Since energy density is not a critical issue in this application, other kind of batteries will be considered as further investigation.

3.1. Supervisory energy management

On the whole, the ICE provides the energy to the system but its role changes according to the power request of boom/bucket pump and wheels. It is possible to consider different situations.

Case 1: The power demand of the boom/bucket system is higher than the level provided by the engine. In this case, the missing mechanical power is obtained from the EM1, through a torque coupler (TC) which allows the mechanical sum of powers, obtaining:

$$P_{EM1} = P_{pump} - \eta_m \cdot \eta_{CVT} \cdot P_{ICE} \tag{1}$$

where P_{EM1} is the mechanical power of the electric machine EM1 that works as a motor. This power is obtained from the battery that has to give, also, the power for the wheels. Therefore, the (positive) electric power of the battery is:

$$P_{battery} = \frac{P_{EM1}}{\eta_{inv,1} \cdot \eta_{EM1} \cdot \eta_{el}} + \frac{P_{EM2}}{\eta_{inv,2} \cdot \eta_{EM2} \cdot \eta_{el}} \tag{2}$$

where P_{EM2} is the power necessary to move the wheel if the CWL is moving that could be negative in case of regenerative braking. Note that eqs. (1)-(2) are valid also when the pump or the wheel request is zero.

Case 2: The power demand of the boom/bucket system is lower than the level provided by the engine. In this case, the mechanical power in excess is directed to the EM1, obtaining:

$$P_{EM1} = \eta_m \cdot \eta_{CVT} \cdot P_{ICE} - P_{pump} < 0,\ P_{battery} = -\frac{|P_{EM1}|}{\eta_{inv,1} \cdot \eta_{EM1} \cdot \eta_{el}} + \frac{P_{EM2}}{\eta_{inv,2} \cdot \eta_{EM2} \cdot \eta_{el}} \tag{3}$$

This power can be either positive (the battery is in discharging) or negative (the battery is recharged).

Case 3: The power demand of the wheels is negative when vehicle is in braking. In this case, part of the current generated by EM2 can be used to recharge the battery:

$$P_{battery} = \frac{P_{EM1}}{\eta_{inv,1} \cdot \eta_{EM1} \cdot \eta_{el}} - \eta_{el} \cdot \eta_{inv,2} \cdot \eta_{EM2} \cdot \left| P_{wheels} \right| \tag{5}$$

The management of the battery is a charging sustaining strategy is performed so that the last value of SOC in the cycle is the equal to the initial one, because an eventual variation would mean an addicted or deducted amount of energy to or from the battery [20]. To implement the charging sustaining strategy, the Y-cycle was repeated 50 times as already explained.

3.2. Engine management and modeling

The engine is kept at a power P_{ICE}=cost along the cycle but is this power level depends on the battery size because of the selected charging sustaining strategy. The required power being the same, the specific fuel consumption depends on the selected speed which is adjusted to match the best efficiency compatible with P_{ICE} for each engine size ([21], [22]). Both engines considered in this work are modeled with a static performance map as in Fig.2c. The map of the scaled engine was obtained with the procedure proposed in [23] and [24].

3.3. Management and modeling of the electric machines

Electric machine EM2 is to meet, at any instant, the power required by the wheels, which is assumed positive in traction and negative in braking. Electric machine EM1 gives the difference between the power required by the pump and the power generated by the engine, at the net of the transmission efficiency.

A wide range of electrical machines is available, depending on the area of application. Generally electric machines could be categorized mainly in to DC and AC machines, synchronous, asynchronous, etc. [18]. In this architecture, permanent-magnet electric machines are considered for both EM1 and EM2 because of the higher efficiency of this kind of motors [4]. To use this kind of motors in particular conditions, and especially during high load application, it is necessary to provide electric motors by a control unit to optimize driving torque distribution.

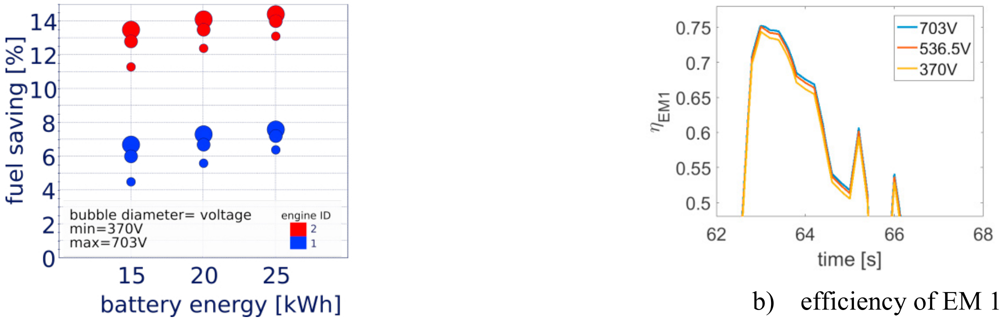
Both machines are modeled using the scaling procedure proposed in [24], starting from efficiency maps of electric machines proposed by Guzzella and Sciarretta in [4] and made available in the QSS toolbox (http://www.idsc.ethz.ch). The maximum efficiencies in motor and generator mode are, respectively, 0.91 and 0.89 Note that the efficiency of each electric to mechanical conversion is affected by the efficiency of the inverter, of the electric machine and the electric connections. The electric connections are assumed to loss 2% of the electric input power independently of the power request. For the efficiency of the inverters, literature curves of its values vs power request are used [25].

3.4. Battery management and modeling

Given P_{ICE}, P_{pump} and P_{EM1}, the battery power is automatically defined from the equations above. The battery is modeled in the present investigation with the Shepherd model and the coulomb counting method [4] to obtain the time histories of current, voltage and state of charge of the battery, which are all dependent on the instantaneous power request. In all the cases described above, it is necessary to check that the state of charge of the battery is between thresholds SOC_{inf} and SOC_{sup} where SOC_{sup} cannot be higher than 100%. For a lithium-polymer battery, the allowed depth of discharge is 80% [26]. Therefore, SOC_{inf} cannot be lower than 20%. Moreover, the maximum positive current to be delivered by the battery must be lower than its nominal discharging C_{rate}. During the charging phase, the (negative) current must not exceed the maximum charging rate allowed for the battery. Note that for the same battery technology (lithium-polymer in this case), these current rating values depends on the internal resistance of the battery.

3.5. Preliminary design

In the design of the power system, the size of EM1 was arbitrary set. Then, a parametric analysis was performed to evaluate the benefit in terms of fuel consumption with two different engines (1: original, 2: scaled), three batteries sizes (15kWh, 20kWh and 25kWh) and three voltage levels (370V, 536.5V and 703V). In all cases, the final state of charge for the battery was equal to the initial one with a tolerance of 0.5%. The maximum battery current in charge and discharge was assumed the same for all cases and equal to 3C and 10C, respectively, where C is the nominal capacity of the battery (energy/voltage). The results are shown in Fig. 4a.



a) fuel saving

b) efficiency of EM 1

(engine =1, battery energy=15kWh)

Fig. 4. Results of the parametric analysis

For the original engine, fuel saving increases with battery energy and voltage and reaches the best values of 7.6% (with respect to the original powertrain) in the case 703V and 25kWh. Note that the same improvement can be obtained by simply replacing the original engine with the scaled one. Combined with the hybridization, the scaled engine allows fuel saving to reach -14.4% of the original power system. However, the strong downsizing could not be compatible with the available diesel technology and with the assumption that the engine best fuel consumption is the same for the two engines since it is well known that engine efficiency improves with its size.

Independently of the engine size, fuel economy improves when increasing either the battery energy or the voltage, because, in both cases, the engine power request is lower. This, in turns, entails a slower engine speed and therefore a better engine efficiency. In fact, for each engine size, the torque is assumed the same for all cases while engine speed is controlled by the CVT.

When increasing the battery energy at constant voltage, the battery available power in discharge increases too, because the battery rating is the same but the capacity increases. This explains why the engine power decreases in this case. On the other hand, when increasing the voltage at constant energy, the battery available power remains the same while its capacity decreases. However, increasing the battery voltage leads to a higher efficiency of the electric machine/inverter EM1 (Fig. 4b), which is the explanation for the lower engine power request.

Using the sizing procedure proposed in [18], the battery volume and mass corresponding to each case was calculated. In all cases, the battery mass is well below the counterweight of the original machine thus confirming that all configurations can be implemented without increasing its overall mass. As for the required volume, it can ranges between 30 liters and 80 liters according to the battery specifications. Since the resulting fuel consumption is affected by the size of the components, a numerical optimization will be performed as next step in the investigation [27], possibly including other duty cycles.

4. Conclusions

The general topic of optimizing the size and the energy management of a hybrid power system for an earthmoving machine is addressed in this investigation by proposing a series/parallel hybrid electric power system for a Compact Wheel Loader and analyzing its performance, and in particular fuel consumption, on a typical duty cycle. The study takes into account two sizes for the internal combustion engines (original and scaled) in order to underline that one of the most important effect of hybridization is the possibility of downsizing the thermal converter, thus allowing it to work at higher efficiency. The results of the simulations show that, by downsizing only, fuel consumption can be reduced up to 8%. However, hybridization is necessary to guaranteed additional power to the power systems and is useful to keep constant the engine working point. A parametric study on the specification of the battery (namely voltage and capacity) showed that hybridization allows fuel consumption to be reduced up to 14% with the scaled engine (with respect to the original power system of the selected CWL).

At the moment, the cost of hybrid electric power systems for earthmoving machines is still too high to justify a considerable access in the market, but the progressive depletion of petroleum-derived energy sources could give companies an impulse to implement such advanced forms of power generation.

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