Design of an On Board Hydraulic Servo-Actuation fed by a Regenerative Braking System

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Servo-System fed by a KERS

***Abstract*—Many conventional truck and working machines are equipped with additional hydraulic tooling or manipulation systems which are usually fed through a mechanical connection with the internal combustion engine, involving a poor efficiency. In particular, this is a common situation for industrial vehicles whose mission profiles involves a relevant consumption of energy by the on board hydraulic systems, respect to the one really needed for only traction purpose. In this work it is proposed an innovative solution based on the adoption of a system aimed to recover braking energy in order to feed an efficient on board hydraulic actuation system. The proposed system is then adopted to a real application, an Isuzu truck equipped with a hydraulic tooling for garbage collection. A prototype of the system has been designed, assembled and tested showing a relevant improvement of system efficiency and the feasibility of the proposed approach. In the paper the proposed solution is presented, showing the simulation models and preliminary validation results including experimental devices assembled to perform the tests.**

***Keywords*—KERS, efficient pump control, hydraulic systems, mechatronics**

1. Introduction:

A. Topic of the Research

Many kinds of -industrial vehicles are usually designed and assembled as customized versions of commercial trucks equipped with electro-hydraulic tooling or manipulation systems devoted to perform specific operations required by the application. Typical applications are related to vehicles used for maintenance and services for urban centres such as garbage collection and other maintenance services as visible in Figure 1~~Figure 1~~.

Currently, most of these vehicles are conventional trucks with an internal combustion engine that is also used to provide the mechanical power needed to feed the board electro-hydraulic tooling and actuation systems.

Especially for vehicle devoted to perform urban maintenance services, the total amount of energy needed by on board hydraulic system is often relevant respect to the one needed for traction purposes mainly for two reasons:

- Overall travelled distances and mean speed of vehicle are quite low.
- Power required by the electro-hydraulic plant is relevant, and the way in which this power is generated and transferred by the internal combustion engine involve considerable amount of losses.

The aim of the work was the investigations of solutions able to substantially improve efficiency and performance of the vehicle including the on board electro-hydraulic servo-system proposing solutions that can be easily adopted not only for new vehicles, but also for the revamping of large fleet of conventional ones currently hold by public administrations.

For these reasons the installation of the proposed systems has to be, as much as possible, simple and also adaptable to different models of trucks.

Figure 1:example of vehicle modified isuzu P75 3.0, modified by Pretto SRL

Typical mission profiles, visible in Figure 3~~Figure 3~~, are associated to urban circuits in which the mean distance between two consecutive stops, where dumpsters have to be collected is few hundreds of meters and the maximum speed is usually not over 50 km/h in order to respect urban speed limits. At every stop, the typical time needed to perform the required operations is usually comprised between 40 seconds to few minutes.

In conventional vehicles electro-hydraulic plant is fed by the internal combustion engine of the truck so it cannot be switched off during a stop involving an increment of fuel consumption and pollution. In particular, in a mission of about 10 hours about 100 stops with a mean duration of around 80 seconds are performed. So the introduction of this system should assure that the motor can be switched off for at least 2 hours, and twenty minutes which represent at least the 20-22% of the duration of the entire mission. Also it should be considered that garbage collection in urban centres is often performed during the night so a significant reduction of the acoustic emission due to the switching off of the internal combustion engine is highly desirable. These data have been obtained by monitoring with an on board GPS localization system the typical behaviour of a truck performing garbage collection in the town of Livorno, Italy.

Considering the over cited mission scenario, authors proposed to fed the electro-hydraulic plant of the vehicle through the electrical energy stored in the battery, which is continuously recharged exploiting the energy recovered during the braking manoeuvre according the scheme of Figure 2~~Figure 2~~.

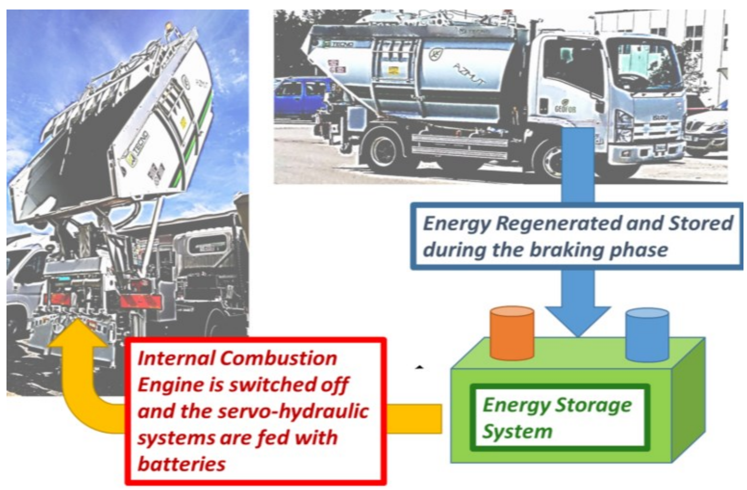

Figure 2: principle of operation of the proposed solution

Due to the encumbrance and cost limitation, it is fundamental to minimize cost and sizing of the energy storage system and of the adopted electrical machines and converters.

As a consequence, a non-secondary task of the activity was also a critical redesign and simulation of the hydraulic plant in order to maximize its efficiency respect to the current solution with affordable costs and intervention respect to the design of conventional plants that have to be modified and "revamped".

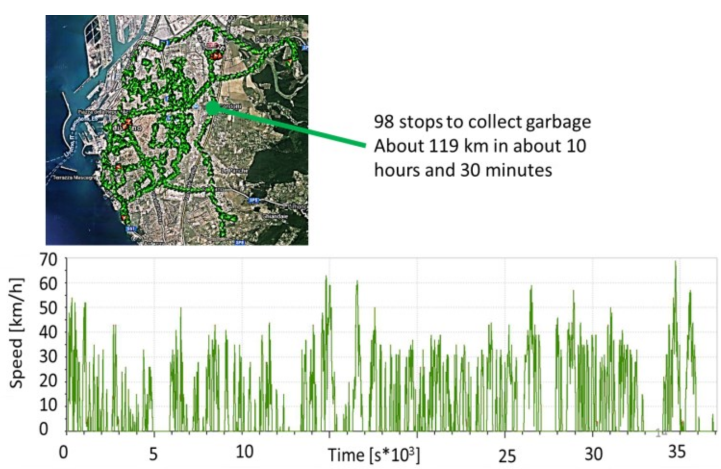

Figure 3: typical speed mission profile of a vehicle performing garbage collection in the Italian city of Livorno Italy

B. State of the Art

For which concern the state of the art there is a wide literature concerning the adoption of electric or hybrid systems able to recovery the kinetic energy during the braking phase. Particularly for the design of hybrid and ground vehicles, this matter is so widely discussed that authors should cite only some review papers as the one of Hannan [1] or Mierlo [2], able to roughly summarize possible solutions.

Also Authors have some previous experience in the development of a full electric vehicle with four in-wheel drive motor [3] and more generally on energy recovery during the braking applied to railway systems [4][5]

Looking at works concerning the life prediction of batteries like the one of Onori [6], it should be noticed that in order to increase life and reliability of accumulators, it is very important to reduce the amplitude of charge and discharge cycles in terms of currents, thermal loads and depths of discharge. In particular authors have focused their attention on works concerning life estimation of Lithium-Ion and Lithium Polymer batteries which are currently the most commonly used for these kind of vehicle applications. For this reason also authors have found interesting contributions and references in many works concerning the estimation of the state of health of batteries using different techniques ranging from impedance measurement [7] to smart filtering of current/power measurements [8][9].

As a consequence, authors have focused their attention to the optimization of the power consumption of the on board servo-hydraulic systems which is the object of many recent publications. In particular looking at review paper concerning this topic authors have found that general reviews on improved efficiency of hydraulic servo-system focused their attention on various way to perform the so called "Pump Control"[10]: speed of actuators is controlled by generating only the oil flow exactly needed for the motion to be performed, minimizing as much as possible laminated and dispersed flows.

This kind of regulation is often called pump control, since the value of generated oil flow is regulated acting on the rotation speed of the pump (fixed displacement pump) or modifying pump displacement (variable displacement pump). In particular a good and very recent review on this matter is represented by the works of Zhongyi Quan [11] and Aly [12].

In particular, the conversion of a wide variety of existing servo-hydraulic machines to pump controlled system is still matter of recent research. One of the most investigated case of application of hydraulic pump is represented by the study of hybrid electro-hydraulic excavators [13],[14],[15].

A more extended approach to the general problem of converting an heavy duty vehicle to an hybrid "series" or "parallel" solutions with pump controlled actuators is studied in the work of Ponomarev [16].

However, as visible in the scheme of Figure 4Figure 4, the general solutions proposed in the work of Ponomarev, involve the usage of at least *n+1* electric drives (including machines and converters) where *n* is the number of degree of freedom controlled by electro-mechanical actuators: in particular a dedicated machine is used to produce electrical energy from the mechanical power produced by the internal combustion engine and each degree of freedom (power conversion) is independently controlled by a dedicated electric actuator (performing pump control). More generally despite to the continuous improvement of electric systems, there is still a wide attention to the optimization of vehicle-fluid servo-system even for traction purposes as in the recent work of Shi[17] which is still focused on the development of hydro-pneumatic systems.

Another general trend in literature to which this work should be reconnected is represented by the investigation of hybrid system in which the energy consumed by an hydraulic plant is provided by a source which is renewable: as example in the work of Campana [18] where is considered the application of renewable sources to a pumping station for agriculture.

Respect to the current state of the art, authors were able to optimize costs by minimizing not only the size of the storage system but also in terms of size of employed electrical machines and drives whose number was reduced to one as better described in the next session of this work.

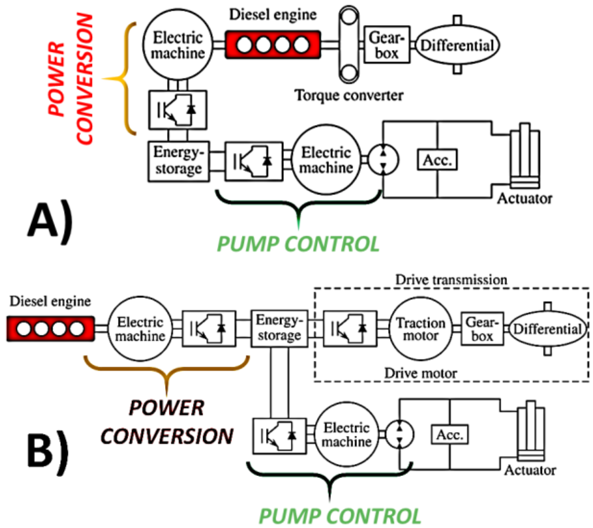

Figure 4: commonly adopted scheme for parallel (A) and series (B) hybrid vehicles with hydraulic actuators controlled by electric pump.

2. PROPOSED SOLUTION AND TEST CASE

A. Proposed Solution

On industrial trucks adopted for garbage collection servo-hydraulic system to lift and manipulate dumpsters are used only when the vehicle is stopped.

As consequence the same electrical machine can be used both to regenerate energy during the braking phase and to control rotation of a fixed displacement pump during the working phase of the plant, the resulting scheme of the proposed solution is visible in Figure 5~~Figure 5~~ and in Figure 6~~Figure 6~~: a PM machine controlled by a four quadrant operation drive is connected through a belt transmission system to the shaft of the vehicle. Connection between the transmission pulley and the PM machine is performed using a clutch that is engaged when the vehicle is moving in order to perform regenerative braking. Also the pulley should be disengaged for vehicle speed exceeding known limits of the electrical machine and increase its reliability and operational life.

The PM motor is also connected to a pump feeding the hydraulic plant, through a flywheel hub. In this way the PM machine is able to transmit torque to the pump only for a known direction sense when the hydraulic plant is activated. A scheme of the mechanical connection between PM machines and loads is also visible in Figure 6~~Figure 6~~. When the hydraulic plant is activated the PM motor is speed controlled. Parameters of the fixed displacement pump are known so the oil flow delivered to the plant should be easily controlled by regulating the speed of the motor and calculated according (1)~~(1)~~:

$$Q = cc\,\eta_v\,\omega_{pump} \qquad (1)$$

In particular in (1)~~(1)~~ the following symbols have been adopted:

- Q is the delivered flow;
- *cc* is the known displacement of the pump
- η_v is the volumetric efficiency of the pump

Proposed solution should be considered as an optimal retrofit kit that should be applied to a wide population of existing trucks with conventional propulsion system, since as visible in Figure 6~~Figure 6~~, motion is transmitted to the PM machine using a transmission belt that should be easily adapted to different vehicle configurations allowing rough installation tolerances.

Since the PM electrical machine is used both for regenerative braking and to feed the hydraulic plant, the sizing of this component is mutually affected by the design of both the systems (kinetic energy recovery system and hydraulic plant) involved in two different functionalities. As a consequence, design of KERS (Kinetic Energy Recovery System) and hydraulic plant should be advantaged by the adoption of models able to reproduce this apparently weak coupling between the two systems.

As visible in Figure 7~~Figure 7~~, the same system should be easily installed with few modifications also on hybrid or pure electric vehicles removing the mechanical connection of the motor (belt and pulley transmission) and the freewheel hub which is not more needed since the rotation sense of the PM motor is always the same. Motor Drive is directly fed by vehicle accumulators or indirectly, using an additional DC-DC converter and a dedicated accumulator.

In this case the proposed scheme should be quite similar to one of the two solutions of Figure 4~~Figure 4~~ depending on the vehicle plant to which the system is interfaced. In particular, there is no need of implementing a customized KERS (Kinetic Energy Recovery System) to feed the system since pre-existing features of the hybrid/electric vehicle plant are exploited.

As a consequence, the novelty of the proposed solution should be summarized in the following three points:

- An innovative electromechanical layout, that, using only one electrical machine is able to perform two different tasks:
  - Operating as a generator. In this way, the electrical machine is used to recover during the braking phase and store in an electrochemical storage system part of the kinetic vehicle energy, thus implementing one kinetic energy recovery system (KERS).
  - Operating as a speed controlled motor. . The same electrical machine can be used to feed a pump able to control an hydraulic plant
- The main advantage of the proposed solution is represented by simplicity since size, cost and number of involved components is minimized respect to more general solutions proposed in literature (one motor, only one actuated clutch). In this way, it was possible to drastically simplify a system by decomposing the mission profile in different phases in which the power flows between components and subsystems is known.
- Innovation respect to application field and system design: elementary components and adopted solutions are aligned with the current state of the art. What makes different the proposed study respect to the state of the art is the application, and the cost effective way that has been adopted. Simple solutions, applied to conventional industrial trucks equipped with hydraulic servo-systems, should be adopted to obtain a cost effective improvement in terms of efficiency, acoustic emissions, overall usability and maintenance.

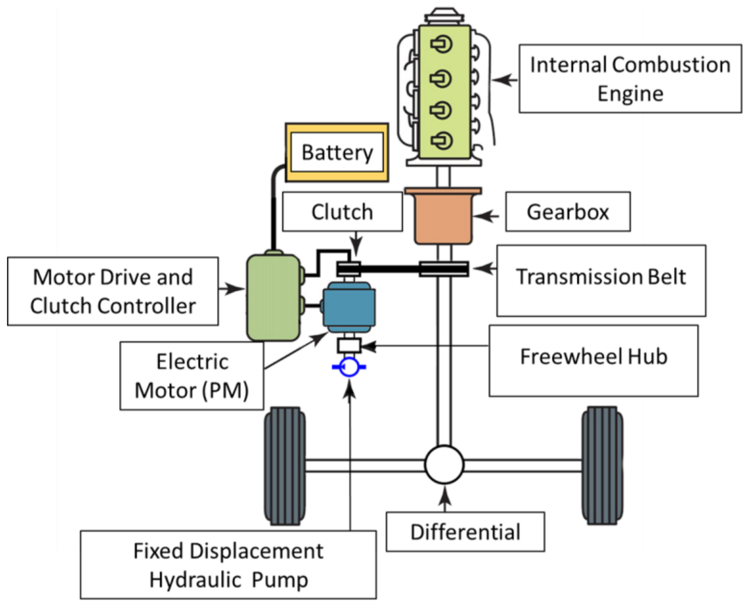

Figure 5: simplified scheme of the proposed solution

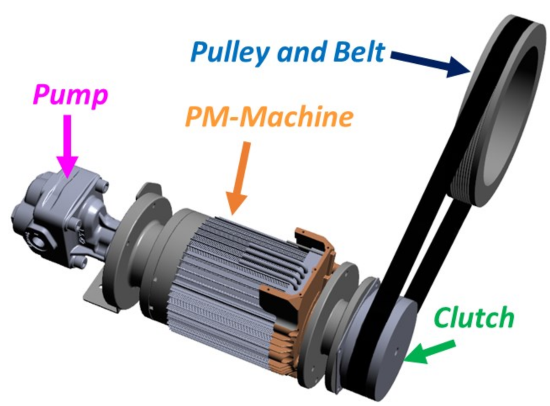

Figure 6: further detail of the mechanical connections between PM machine and loads

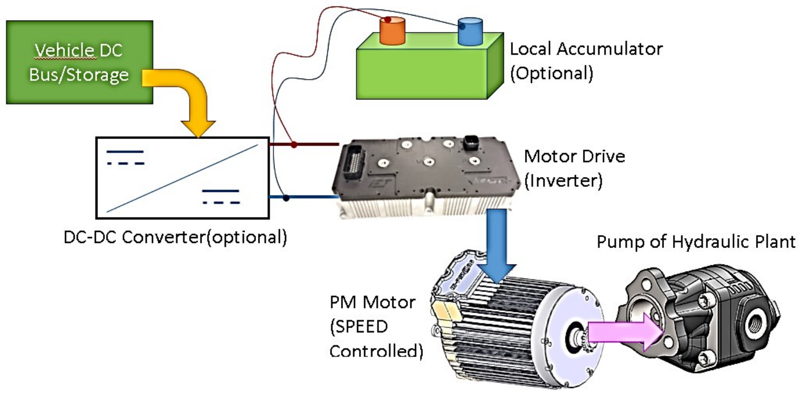

Figure 7: direct connection of the hydraulic plant to the electric plant of an hybrid or electric vehicle

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B. Proposed Test Case

The proposed system is installed on the chassis of an ISUZU P3 75 3.0 truck, whose main features are described in Table I~~Table I~~.

As visible in Figure 8~~Figure 8~~, the chassis of the proposed test case has a quite common layout that is often adopted on many commercial vehicles, for this layout encumbrance and more generally positioning of the proposed solution make quite easy the implementation of the proposed solution on a wide range of different trucks.

As visible in Figure 9~~Figure 9~~ and in Figure 10~~Figure 10~~, in order to perform lift and manipulation of dumpsters, the truck is equipped with different articulated systems able to perform six different motions through the control of 10 hydraulic actuators:

- Motion 1: cylinder clamp the dumpster until end stop;
- Motion 2: preliminary lifting;
- Motion 3: dumpster lifting;
- Motion 4: dumpster tipping;
- Motion 5: repeat steps (1,2,3,4) backward;
- Motion 6: progress of the chassis;
- Motion 7: shovel closing;
- Motion 8: return of the chassis;

Finally, when the collecting tank is full, it is periodically lifted up in order to dump collected garbage performing the movement describe in Figure 10~~Figure 10~~.

Table I: Main Parameters of the truck Isuzu P3 75 3.0

Symbol	Quantity	Value [Units]
M	Vehicle Mass (full load approximated)	7500 kg
C	Displacement	2999 cc
M_{max}	Max Motor Torque	375 Nm (1600-2800 rpm)
P_{max}	Max Power	110 kW (2800 rpm)
τ_{g1}	Ratio of First Gear	5.979
τ_{g2}	Ratio of Second Gear	3.434
τ_{g3}	Ratio of Third Gear	1.832
τ_{g4}	Ratio of Fourth Gear	1.297
τ_{g5}	Ratio of Fifth Gear	1.000
τ_{g6}	Ratio of Sixth Gear	0.759
τ_{gr}	Ratio of Reverse Gear	5.068
T_d	Ratio of the differential	5.571
V_{max}	Max Speed (limited electronically)	90 km/h

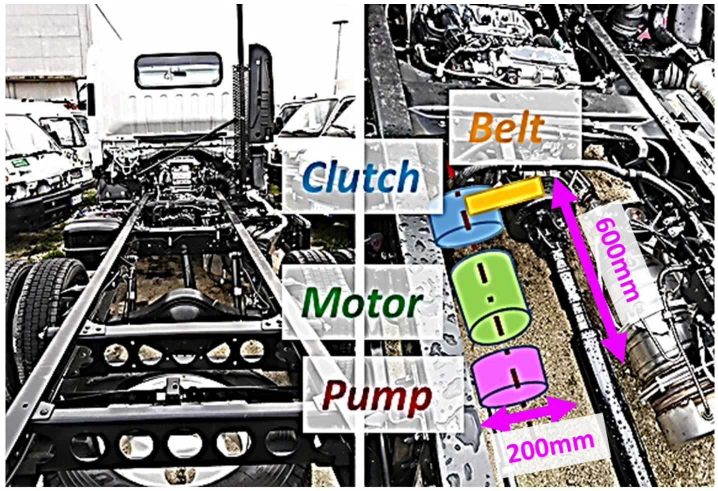

Figure 8: Approximated Encumbrances of the proposed solution on a Isuzu P3 75 truck

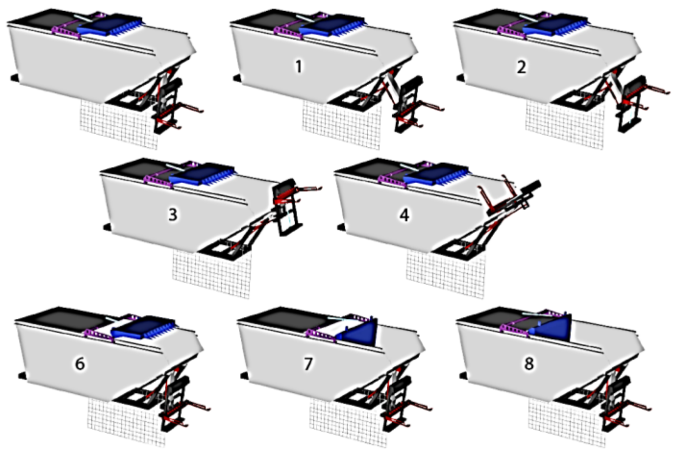

Figure 9: list of the performed motions

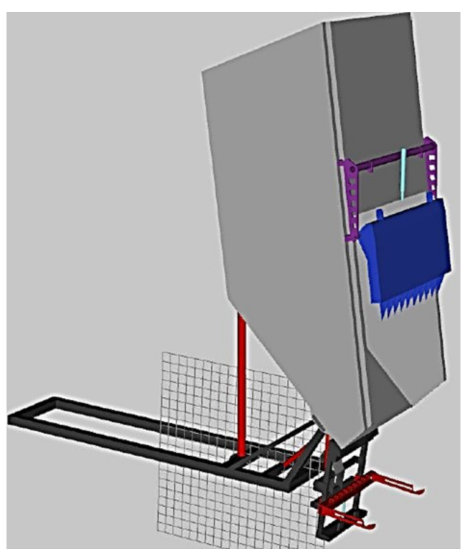

Figure 10: lifting and empting of the collecting tank

In the conventional plants, usually installed on this kind of vehicles, the manipulation of the dumpster is decomposed in a sequence of individual motions each corresponding to a single degree of freedom which is actuated by one or more parallel connected

actuators: to individually control the i-th motion only the i-th hydraulic actuator has to be fed, while the other ones are blocked by end runs and/or by incompressibility pressurized oil.
In this way, the traveling speed v_i of each of the i-th linear actuator is controlled by regulating the corresponding inlet flow Q_i. according relation (2)~~(2)~~

$$v_i = \frac{Q_i}{A_i} \qquad (2)$$

In (2)~~(2)~~ the symbol A_i is adopted to identify the corresponding equivalent area of the i-th actuator.
In most of the conventional plant regulation of the flow Q_i delivered to each actuator is performed according the simplified scheme of Figure 11~~Figure 11~~: a fixed displacement pump is directly connected to the internal combustion engine with a constant rotational speed that can be easily regulated considering the equivalent inertia of the motor and its relatively large torque capability respect to the connected load represented by the pump. As a consequence delivered flow Q is almost constant and it is regulated by a flow control valve which directly recirculates a part of the flow Q_r in order to deliver the desired value of Q_i to the controlled load according (3)~~(3)~~.

$$Q = Q_i + Q_r \qquad (3)$$

Oil recirculation to tank introduces a loss of Hydraulic power W_d which is proportional to the recirculating flow Q_r according (4)~~(4)~~:

$$W_d = \frac{Q_r P}{\eta_t} \qquad (4)$$

In (4)~~(4)~~ symbol P represents the hydraulic head pressure of the pump (neglecting small or null pressurization values of the tank) and η_t represents the total/energetic efficiency of the pump. Considering a double chamber/effect cylinder also flow controlling/safety devices should be installed to control the speed of the load especially during braking/deceleration phases or in the return run since in this case the sense of the load should be inverted. This solution involves small additional losses which are tolerable mainly for two reasons: transients are usually quite smooth and during the return phase the dumpster is usually empty so the load is quite smaller and almost known.
This simplified scheme is one of the most commonly adopted in conventional solutions in order to optimize costs, reliability and robustness of the control loop.
However, in the proposed applications an increase of the efficiency of the oil plant should lead to a significant size reduction of the energy storage system with consequent benefits in terms of costs, encumbrances and reliability (a less loaded battery should suffer lower aging effects).
For this reason, authors proposed the solution represented in the simplified scheme of Figure 12~~Figure 12~~: the speed of the fixed displacement pump is directly regulated by modifying the rotational speed of the PM motor so there is no need of recirculating to tank a part of the flow Q_r being Q_i almost equal to Q. In this way most of the plant is always equal to the original one and the modification mainly affects only two components:

- The flow control valve, used to recirculate the flow Q_r which is removed.
- The pump, whose fixed displacement should be modified to optimize the sizing of the connected PM machine (alternatively a reduction gearbox between motor and pump).

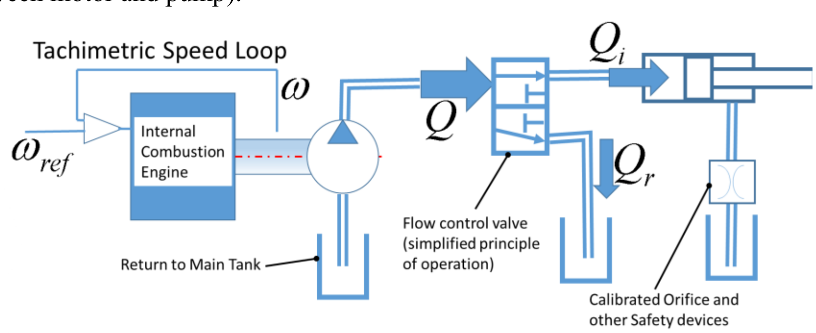

Figure 11: simplified scheme, principle of operation of a conventional solution respect to the control of a single degree of freedom

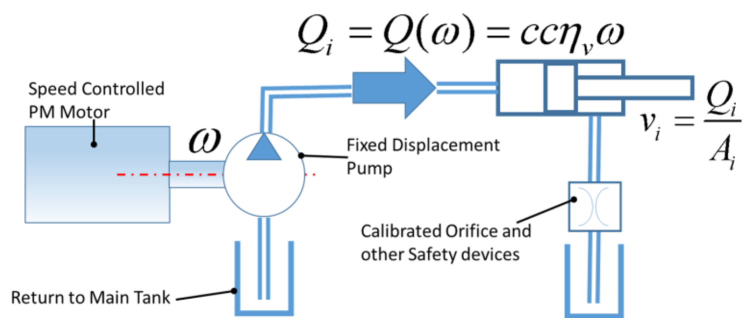

Figure 12: simplified scheme, principle of operation of the proposed solution respect to the control of a single degree of freedom

Further power savings should be obtained by adopting hydraulic schemes that allows the regeneration of hydraulic power such as the one considered in [15] and [19][17].
For the proposed application, authors avoided this kind of solutions mainly for the following reasons:
• more than a half of the power required by the hydraulic plant is due to irreversible operations in which the power is dissipated or is almost impossible to be recovered: as example some actuators are devoted to compress the /compact the garbage loaded on the truck, other actuators perform clamping operations for which the energy cannot recovered;
• conversion efficiencies further reduce the percentage of energy that should be recovered;
• finally, in order to fully exploit the hydraulic regeneration of power, some further modifications have to be introduced so benefits and drawbacks have to be further evaluated. considering also cost and reliability specifications.
As a consequence, authors believe that the application of this kind of solutions should be considered as a further optimization of the system that should be probably the object of future works.

3. Modelling

A. Hydraulic Model of the conventional plant

Aim of this activity was the developments of models able to evaluate energy consumption of on board hydraulic servo-system used to lift and manipulate the dumpsters.

Models of both conventional plant and proposed innovative solutions have been assembled using a commercial software, Amesim™. All the presented models have been assembled from scratch. So the results of the presented activity were also a demonstration of how an innovative use of modern simulation tools can be very important for rapid prototyping of electromechanical systems, by using resources that are compatible with small scale productions.

Authors have started their activity modelling the conventional hydraulic plant in order to validate the tool with experimental tests performed on existing unmodified vehicles. Thanks to the data kindly supplied by the developer of the conventional hydraulic plant, authors have assembled a full hydraulic model, visible in Figure 13Figure 13, according to the following assumptions:

- Pump Model: the pump is modelled as a flow source whose reference flow is proportional to the rotating speed ω, taking count of volumetric efficiency η_v, which is a tabulated function of head pressure and delivered flow. The corresponding torque demand is then evaluated from required hydraulic power taking count of the total efficiency of the valve η_t, which is also a tabulated function of pressure and flow.
- Modelling of Pipes and Lumped Hydraulic elements: each hydraulic pipe branch is discretized as single lumped Resistive (R) and Capacitive (C) element taking count of equivalent compressibility effects introduced by friction losses on pipes and compressibility effects due to both oil compressibility and pressure induced deformations of pipes. Inertial effects which are usually with lumped mono-dimensional elements (I) are neglected considering the low dynamical behaviour of the plant. The adopted approach is quite common in literature [20][18] and also adopted by authors for the simulation of plants and fluid networks with uncompressible [21][19] compressible fluids[22][20] or multiphase one, such as steam [23][21].
- Dynamical behaviour of the controlled 4/3 valves: valves are modelled considering the equivalent response of a second order system (eq. valve eigen-frequency at 20 Hz) as often proposed in literature [24][22],[25][23],[26][24].
- PLC/Control logic: valves are controlled in order to produce the desired sequence of motions by an industrial PLC which decides the current valve configuration according the position feedback of controlled axis. Control logic is implemented in term of equivalent state-flow chart [27][25].
- Customized Hydraulic components: for some lumped components of the real plant there was no equivalent model in the AMESIM library. In particular authors have to assemble customized models (Amesim Supercomponents) of over-centre valves and flow regulation one which are shown respectively in Figure 14Figure 14 and in Figure 15Figure 15.
- Multibody Model: loads applied to each cylinder are simulated using a complete model of the articulated system used to lift and move the dumpster. Friction on joint is not considered (only a small viscous damping is applied in order to prevent numerical chattering). Inertial properties and weights of each body are calculated from three-dimensional CAD models of components.

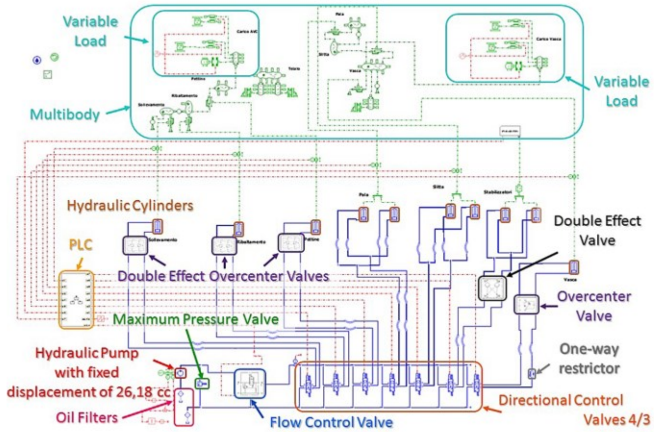

Figure 13: (conventional hydraulic plant)

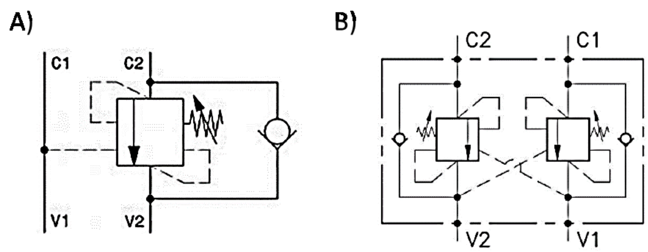

Figure 14: Equivalent scheme single (A) and double(B) over centre valves (Custom Amesim Super-Component)

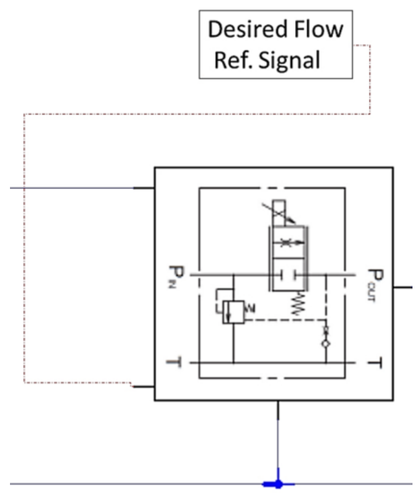

Figure 15: Control Flow Valve (Equivalent Supermodel)

B. Model of the Proposed Solution

Proposed solution, described in Figure 5~~Figure 5~~ involves the modelling of two main systems:

- A modified hydraulic plant;
- The KERS;

As previously said the two sub-systems share the same electric motor drive and energy storage

- A modified hydraulic plant sub-model: this model is devoted to the calculation of the behaviour of the hydraulic servo-system and to the calculation of required mechanical torques and power required to fed the pump.
- KERS Sub-Model: according simulated vehicle dynamics, the energy recovered and stored on electrochemical storage is calculated. Since from the hydraulic model are known reference torque and speed required by the pump when the vehicle is stopped this load can be applied to the motor verifying the effects in terms of battery discharge and life.

1) Modified Hydraulic Plant Sub-Model

The innovative solution differs from the original one only for the removal of the flow control valve and for the different sizing of the fixed displacement pump, which is moved by an electric PM motor according the scheme of Figure 5~~Figure 5~~.
In this model, visible in Figure 16~~Figure 16~~, only the mechanical behaviour of the motor in terms of exerted torque limitations and inertia are evaluated. In this way the model is able verify if the target performances of the motor are good enough to obtain the required service. Calculated motor torque and speed are then passed to KERS Sub-Model to verify the consequences in terms of electrical energy consumptions.

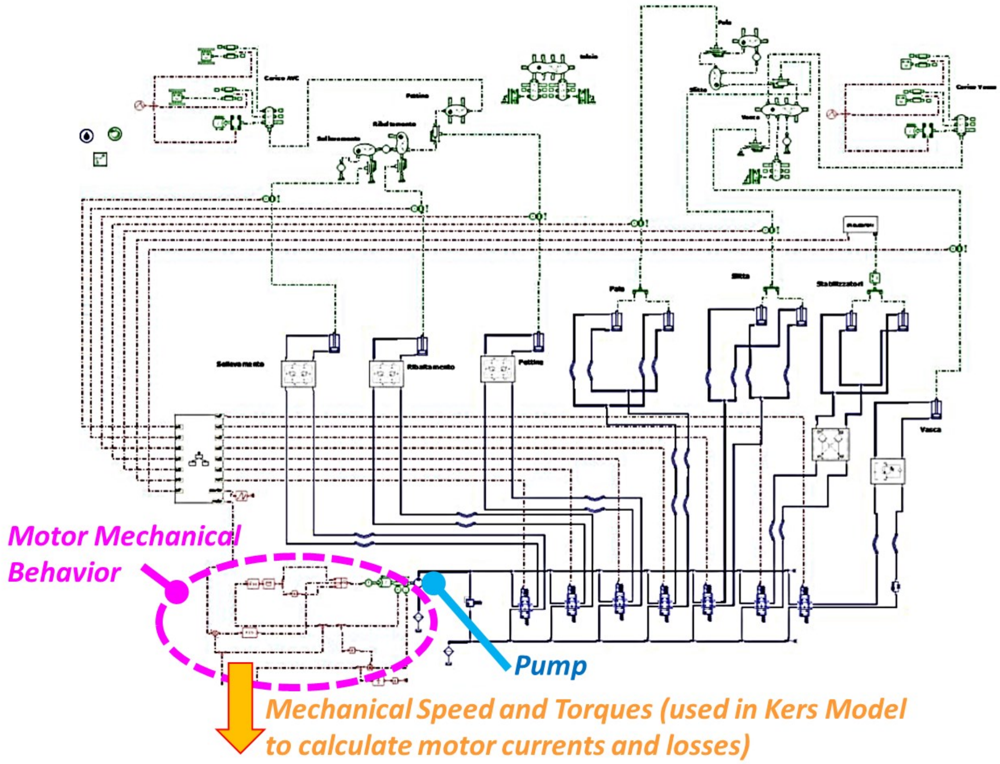

Figure 16: Modified Hydraulic Plant Model developed in LMS Amesim

2) KERS Sub Model

The KERS submodel visible Figure 17~~Figure 17~~ is able to simulate the dynamical behaviour (block planar vehicle dynamics) of the benchmark test vehicle Isuzu P3 75 whose main data are described in Figure 1~~Figure 1~~and in Table I~~Table I~~. Desired mission profiles in terms of speed are reproduced (autopilot block), considering vehicle feature. Regarding the internal combustion engine authors assumed the torque behaviour corresponding to Figure 18~~Figure 18~~.
For the electric drive and PM machine system assumed the hypothesis of a direct connection with the pump, so required currents and power can be directly calculated using a model of the PM brushless machine whose efficiency is a tabulated function of exerted speed and torque.
In order to verify thermal overload conditions, the simplified model (5)~~(5)~~ is considered for the calculation of motor temperature *T*:

$$T = aI^2 - a\left(I^2 - I_0^2\right)^{-bt} \quad (5)$$

In (5)~~(5)~~ symbols I and I_0 are respectively actual and reference current values of the motor; t represent the time while a and b are two parameters tuned with best fit criteria respect to limited available data from motor supplier.
Consumed and regenerated current and energy calculated by the model are used to calculate the corresponding behaviour in terms of battery SOC (State of Charge) and optionally battery SOH (State of Health). The battery is supposed to be Lithium-Ion one. Corresponding Dynamic and Aging models of the battery are described in the references [26-30]. The implemented control logic (block Kers Logic) visible in Figure 17~~Figure 17~~ is implemented in terms of state-flow charts taking count of the following inputs: Speed, State of Charge of the Battery, Performed Manoeuvre (Traction, Braking Coasting), Thermal Overload of the PM-Machine.

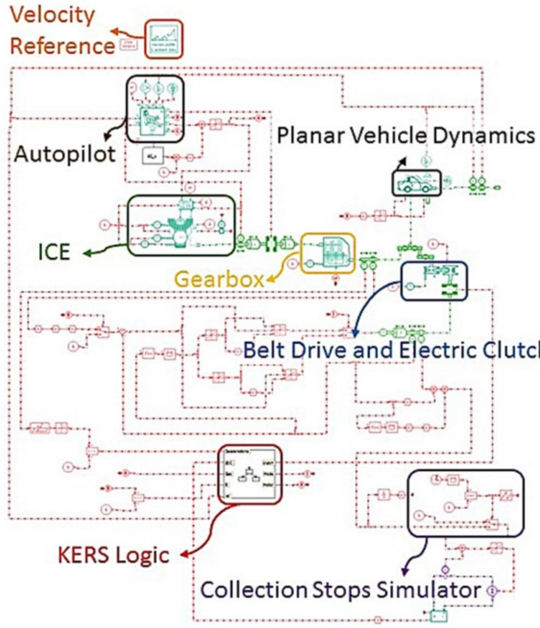

Figure 17: Amesim vehicle model

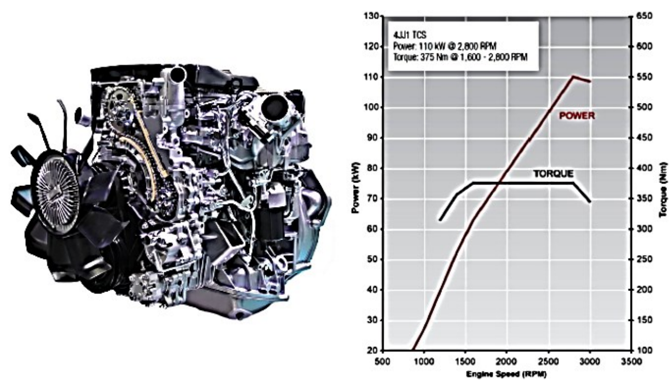

Figure 18: Diesel Motor installed on Isuzu P3 75 Motor

4. Preliminary Model Validation and Preliminary Experimental Activities

Preliminary experimental activities play a key role in the development of the system mainly for two reason: first, the hydraulic plant model whose calibration involve the setting of hundreds of parameters has to be validated. Also a good calibration of the system involves the knowledge of a typical mission profile, in order to avoid unrealistic assumptions in the preliminary sizing of the system.

For this reason, authors developed a compact and cost effective acquisition system visible in Figure 19~~Figure 19~~: The system fed at 24V and sealed in a IP66 Box was designed to acquire and save data on a SD memory card at a maximum frequency of 10 Hertz. In particular the acquisition module is able to localize the vehicle through a dedicated GPS system the whole list of acquired sensors is listed in Table II~~Table II~~.

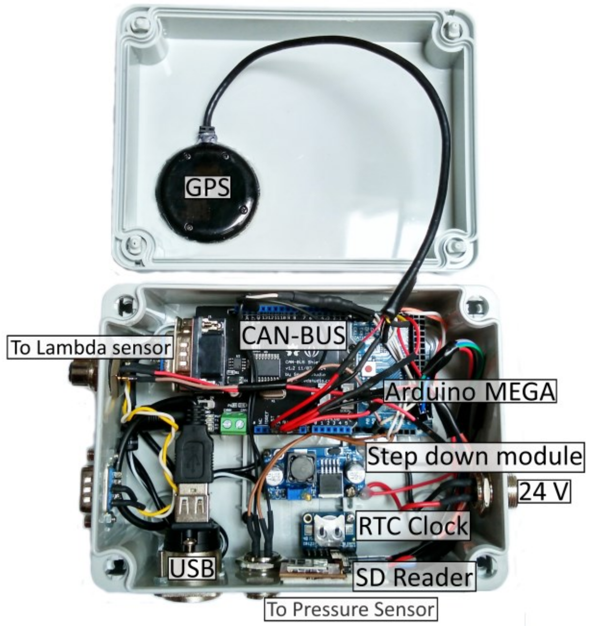

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Figure 19:Customized Acquisition Module

Table II: Low cost monitoring board adopted for

Acquired Measurement	Sensor/interfaced hardware	Signal/ Communication Protocol/Signal
Position	GPS	serial
Long. Speed	Vehicle ECU	CAN BUS
Performed maneuver (traction or braking)	Vehicle ECU	CAN BUS
Inlet air mass flow in the motor	Debimeter	dedicated
Oxygen in Exhaust Gas/Stechiometric Ratio	Lambda Probe	dedicated
Head Pressure in Hydraulic Pump	Pressure Sensor	Analog Voltage
Speed of electric PM machine	Motor drive (encoder)	CAN BUS
Motor Temperature	Motor drive (thermo-couple in windings)	CAN BUS
Inverter Temperature	Motor drive	CAN BUS
Battery State of Charge	Motor Drive/BMS	CAN BUS
DC link current and voltage	Motor drive	CAN BUS
Electromagnetic friction state (engaged/disengaged)	Vehicle ECU	CAN BUS
State of The Hydraulic Plant	PLC (logic controller of the hydraulic plant and related position feedback sensors)	CAN BUS
Oil Temperature (TANK)	PLC (logic controller of the hydraulic plant interfaced with a temp. sensor)	CAN BUS

The experimental board described in the previous section was then installed on an existing truck equipped with the conventional hydraulic plant described in Figure 13~~Figure 13~~ and performing its service activities in the town of Livorno in order to obtain measured mission profiles like the one described in Figure 3~~Figure 3~~ that were quite precious for the preliminary sizing of the innovative solution.
Also Authors performed some preliminary calibration and validation tests by executing the lifting sequence described in Figure 9~~Figure 9~~ with a loaded dumpster. Tests were executed on a truck equipped with the conventional plant. During the test head pressure of the pump is measured and compared with corresponding simulation results as visible in the example of Figure 20~~Figure 20~~: it should be noticed that there is a good agreement between experimental data and simulation results. In particular, the model was able to fit steady state values of head pressure corresponding to a good identification of mean load parameters including friction losses on valves and pipes. On the other hand, some clear differences should be noticed on transients associated to valve

commutation and to the motion start on joints. In particular, simulated valve commutations in the model produce high frequency oscillations (hundreds of Hz) on simulated pressure which cannot measured by the real sensor due to lack of bandwidth. Also in the real plant, pressure peaks with durations between 0.1 and 0.5 seconds are observed: these peaks are associated to the motion start of actuators. These phenomena should be explained considering that the articulated system is affected by non-linear friction and elastic compliances especially on joints. In particular, in the real plant the transition between static and kinetic coulomb friction values is associated to a characteristic stick-slip transient. Measurements were performed using the experimental layout visible in Figure 21~~Figure 21~~.

During the tests also the tank temperature is observed in order to avoid errors and uncertainties on oil properties.

However. for the purpose of this work which was the preliminary sizing of the system, obtained results were good enough to validate the model for the desired purpose: a reliable tool to properly size the new plant and to evaluate overall energy consumptions and efficiency.

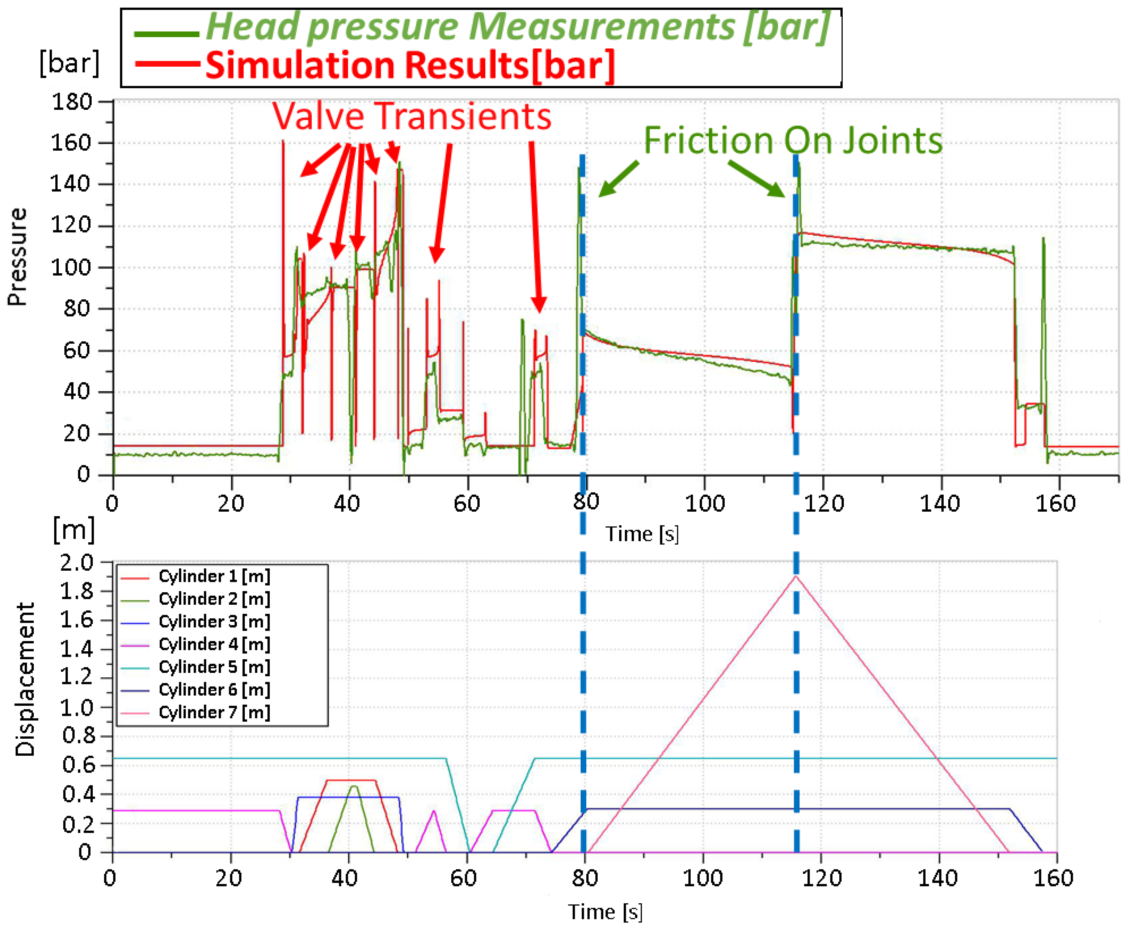

Figure 20: comparison between experimental results and simulation results in terms of the measured head pressures and corresponding motion of cylinders (full loaded dumpster)

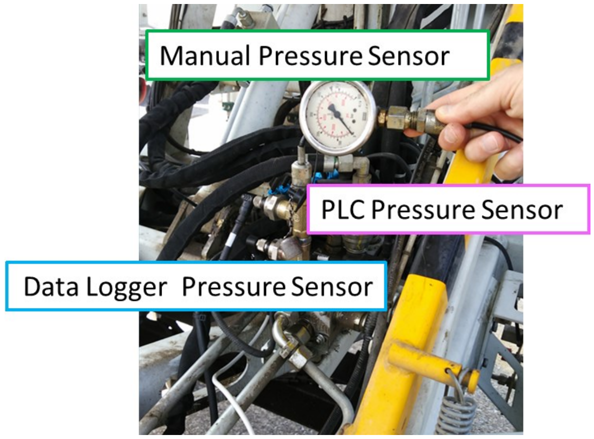

Figure 21: preliminary validation activities, head pressure measurements

5. Preliminary Sizing And Simulation Results Of the Proposed Solution

A. Coupling with the hydraulic Plant

From simulations performed on the validated model of the conventional hydraulic plant, it was possible to estimate the amount of power needed to perform a complete lifting cycle of a dumpster for both conventional and innovative plant: from preliminary calculations the mean power required during a test was evaluated as about 2000-2500 W for the innovative solution and 4000-5000W for the conventional one. An overload factor of 2, intended as the ratio between maximum load and medium one, was considered. Differences in terms of required power between the two solutions are justified by the higher efficiency of the proposed innovative solution with hydraulic pump control.

In order to minimize the size of the electrical machine a power based design was chosen: the chosen machine is a PM motor able to exert a continuous power of about 4-6 kW at 2000-3000 rpm which is at least two times higher respect to the load demand of the innovative plant. Speed specifications were chosen in order to not penalize to much the efficiency of the new pump which is directly connected to the motor respect to the original one that was designed to operate at a lower operating speed (1000rpm) with a higher fixed displacement (about 26 cm^3 respect to 12 cm^3 of the new solution).

Difference between calculated power for conventional and innovative solutions should be easily explained looking at the comparison in terms of delivered flows and pressures.

In particular, as visible in the simulated pressure profiles represented in Figure 22~~Figure 22~~, in the conventional solution flow regulator valve introduces pressure losses (10-20 bar) which are relatively quite important especially on partial loads corresponding to smaller or empty dumpsters.

Also looking at flows for some elementary motions as the one visible in Figure 23~~Figure 23~~ it should be noticed a clear difference between the conventional solution and the pump controlled one: in this example of mission profile more than half of the almost constant flow produced by the pump of conventional solution is recirculated to tank in order to control actuator speed. This can be easily explained considering that the conventional plant is designed to satisfy with its constant flow the maximum oil demand of the plant. On the other hand, the proposed pump controlled system is able to exploit the wide operating speed range of the controlled PM motor.

Considering a pressure loss corresponding to about 10% of head pressure and a percentage of recirculated flow for the conventional solution which is near to 40%, it's possible to understand the reason of different power requirements between conventional and innovative solution since the required mechanical power of the pump W can be calculated according (6)~~(6)~~, having adopted almost the same symbols and notation of (4)~~(4)~~ and (3)~~(3)~~.

$$W = \frac{QP}{\eta_t} \qquad (6)$$

It should be also noticed in Figure 22~~Figure 22~~ that the adopted design of the innovative solution involves that nominal torque of the motor (16.5Nm) corresponds to a delivered head pressure of about 65-70 bar, as a consequence higher forces involve an overload of the motor corresponding to a plant pressure of about 100-120 bar, corresponding to a required torque of about 30 Nm. However, as visible in the graph of Figure 24~~Figure 24~~, the motor should be overloaded (according specifications of manufacturer) for at least 60 seconds exerting a continuous pressure of about 190 bar that the plant cannot reach in real operating conditions for the intervention of safety pressure limitation devices.

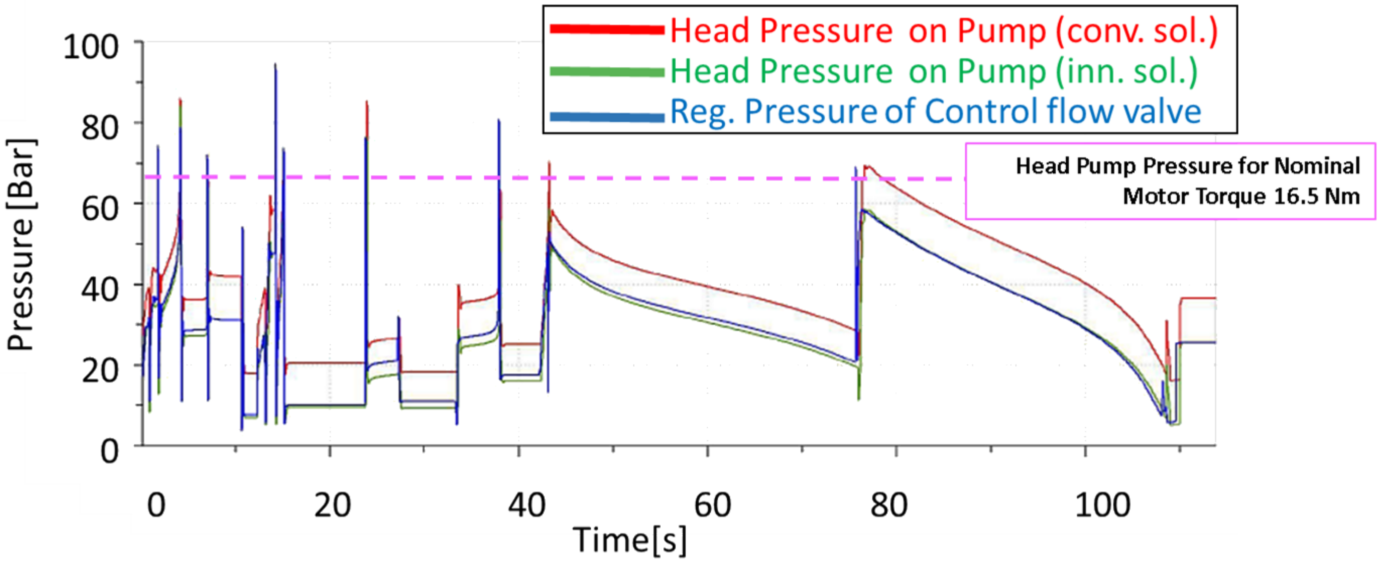

Figure 22: simulation of pressure behaviour (smaller dumpster or partial loaded)

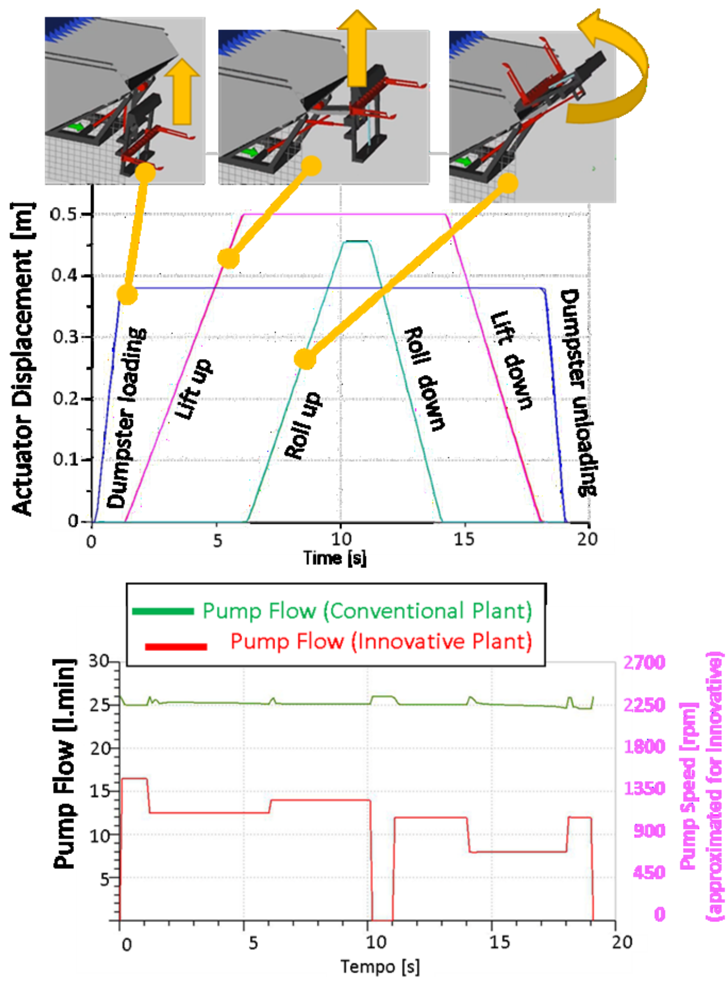

Figure 23: comparison of the pump delivered flows (conventional vs. innovative solution)

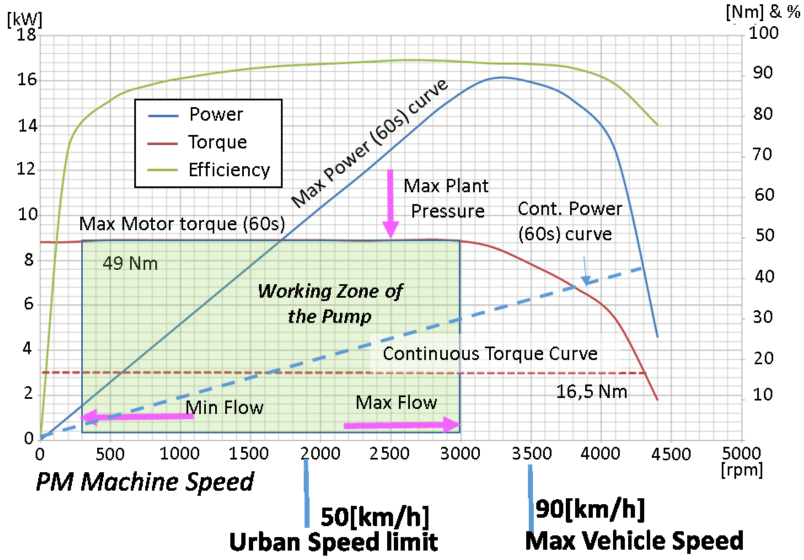

Figure 24: Main Performance of the selected machine versus coupled loads and vehicle operative conditions.

B. Design of KERS System

According the simplified scheme of Figure 5~~Figure 5~~ and Figure 6~~Figure 6~~, the PM machine is linked to the transmission shaft of the vehicle through a constant ratio belt-pulley transmission system. The transmission ratio of the belt-pulley system is about 1:2 in order to obtain an optimal sizing condition of the system described in Figure 24~~Figure 24~~: maximum speed of the vehicle corresponds to the maximum of regenerated power exploiting all the available operational range of the motor. Also with the adopted transmission ratio it is possible to perform a braking energy recovery at the speed of 50 km/h a power between a minimum of 3-4 kW and a maximum of about 10 kW (considering continuous or peak performance of the PM machine, as example)). In this way the system is designed to share the same power both for regenerative braking and actuation of hydraulic servo-system, showing a symmetrical behaviour in the two operation quadrants. In this regard, the electrical machine has been primarily sized to correctly feed the pump. Additionally, the same machine is also used also to implement energy recovery during braking. Naturally, braking power is much higher, thus only a small fraction of it can be managed by the considered electrical machine.

In particular looking to the typical mission profile of Figure 3~~Figure 3~~, it should be noticed the high frequency of braking manoeuvres which make this sizing quite generous as confirmed by simulation results shown in next section of this work: higher statistical occurrence of braking involve an higher quantity of recovered energy, being the power consumed by the hydraulic plant substantially proportional to the number of collected dumpsters.

It should be noticed that by further increasing the ratio of the transmission belt is still possible increase the amount of regenerated power respect to vehicle speed: as visible in Figure 24~~Figure 24~~, at 50km/h the PM generator should work at about 1900 rpm and the maximum power that can be managed by the system is about 9-10kW., by changing the ratio of the pulley, it's possible to further increase the corresponding rotation speed to the nominal one (3000-3500rpm) corresponding to about 16kW. In current implementation it was preferred a lower speed of rotation of the motor in order to assure a more cautious design of the clutch.

It should be noticed that the simple transmission system adopted by authors, simplifies the installation of the proposed solution on different vehicles. However, gearbox optimization strategies like the one proposed by Li [31] cannot be applied . So the above described optimization of the belt transmission ratio is very important for a correct sizing of the system.

Authors preferred to completely separate the proposed system respect to the vehicle electric plant mainly for two reasons:

- In this way a failure of the system proposed by authors has limited or null consequences the rest of the vehicle, failure propagation effects are limited to the servo-hydraulic plant used to lift the dumpsters; the capability of the vehicle to reach a repair workshop is not compromised.
- The truck proposed in this study is a benchmark test case, the proposed system has to be installed with few modifications on almost every compatible vehicle which should have slight different features. For these reason, authors have tried to simplify as much as possible the proposed plant in order to make easier the customization for different vehicles.

The proposed regulation logic of the KERS system is visible in the scheme of Figure 25~~Figure 25~~, regenerated torque reference M_{ref} is a function of four parameters which are respectively the vehicle traveling speed V, Longitudinal effort request $X_{\%}$, estimated battery SOC (State of Charge), thermal over-temperature diagnostic of motor and drive system:

- *Speed V*: currently the system is activated only for urban mission profiles, so motor clutch is disengaged for speed higher than 50 km/h corresponding to current urban speed limits. In case of clutch failure or if a different control configuration is chosen the motor can operate for speed which are far higher respect to the maximum allowed speed of the vehicle (90 km/h)

- *SOC* of the battery: regenerative braking is activated if the SOC is under 95%, being admissible values of SOC between 0 (battery completely discharged) and 100% (battery fully charged). Applied regenerative brake Torque is a configurable parameter that should optimized according service specifications. This peak value is indicated in the flowchart of Figure 25~~Figure 25~~ "Maximum Braking Performance". In Figure 25~~Figure 25~~ it supposed equal to the maximum peak torque which should be defined as a value between 16 Nm (continuous performance of the motor) and 49 Nm (Overload that can be maintained for 60 s) according the chosen calibration of the system. Currently if the braking manoeuvre is prolonged to more than 60 s the exerted braking torque is lowered to a safer value (16Nm) that can be exerted continuously. The same performance reduction (braking torque lowered to 16Nm) is applied if a thermal overload warning is detected (temperature of both motor and drive is monitored).
  In the flowchart of Figure 25~~Figure 25~~, the cautious value of braking torque that is applied to avoid braking overload during prolonged regenerative braking is called "Cautious Braking Continuous Performance". However, for a battery SOC under a 15% regenerative braking is also applied during a traction manoeuvre. In this way possible SOC values are restricted to a range between 15 and 95% in order to accelerate aging of the batteries [28]~~[26]~~[29]~~[27]~~ and to assure a minimal charge level to perform lifting and manoeuvring of dumpsters. In this case, the duration of this recharging phase cannot be foreseen by the system. Also an excessive braking should penalize traction performances of the vehicle. For all these reasons, the applied regenerative torque during the traction phase is always limited to the minimum value corresponding in the flowchart of Figure 25~~Figure 25~~ to the "Cautious Braking Continuous Performance". Finally, In order to avoid excessive chattering of the system respect to the 95% threshold, a hysteresis of few percentage points is added (2%). This is a feature that is neglected in the simplified flowchart corresponding to a simple relay block in the corresponding Amesim™ Implementation.
- Longitudinal effort demand $X_{\%}$: this state represents the desired manoeuvre of the urban driver assuming a range from *-100%* (full braking required), to *100*% (full accelerator throttle) being *0* the state in which no command is applied. Currently if the Traction effort demand is higher than 80%, regenerative braking is switched off in order to assure the maximum vehicle performance in a situation in which the human driver clearly desires the maximum performance of the vehicle. In the flow chart of Figure 25: KERS, flowchart representation of the simplified adopted control logic.~~Figure 25: KERS, flowchart representation of the simplified adopted control logic.~~Figure 25~~Figure 25~~ if the value of performed manoeuvre is null (coasting) or negative (braking) the equivalent Boolean state "Braking" has a "true/yes" value.

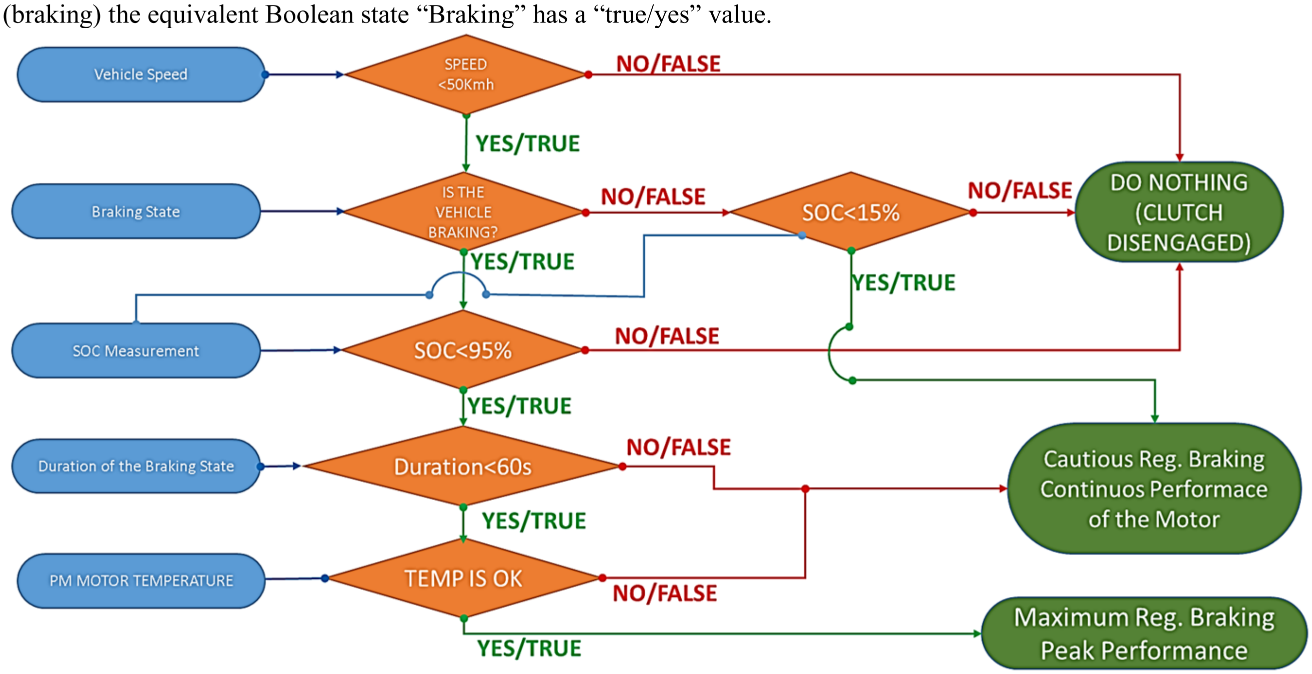

Figure 25: KERS, flowchart representation of the simplified adopted control logic.

The application of an additional braking force on the rear axle of the truck, should cause consequences on longitudinal and lateral stability of the vehicle especially with degraded adhesion conditions, so many recent works are also focused on the design of optimal blending and control strategies [34]~~[31]~~,[35]~~[32]~~.
However, for the proposed application traveling speed is quite low (under 50 km/h) and the torque applied by the KERS system are quite negligible respect to pneumatic braking, so an important advantage of the proposed solution is the limited impact in terms of modification of on board subsystems (braking plant, ABS, etc.).
It is important to notice that proposed control logic of the KERS is very simple, and obviously more complex regulators should be implemented. However, the only aim of the proposed logic is to demonstrate in a clear way the feasibility of the system, leaving to further optimization activities the development of more sophisticated control logics.

C. Sizing of the energy storage system

Using both the models of hydraulic plant visible in Figure 16~~Figure 16~~ and the one of the KERS interacting with the vehicle (Figure 17~~Figure 17~~) it was possible to evaluate typical energy and power flows to properly size the battery. In particular authors starting from power flows analysis of the proposed system were able to adopt a very cheap and compact energy storage system, whose main parameters and are briefly described in Figure 26~~Figure 26~~ and in Table III~~Table III~~ .

In particular the proposed solution is considered very robust respect to very harsh employment conditions (variable temperature, vibrations) since thanks to the high efficiency of the hydraulic plant the total energy required to perform operations, the complete working cycle regarding the manipulation of a dumpster is equivalent to about the 1-2% of the whole nominal energy of the battery with positive consequences in terms of aging and reliability, i.e. reducing the SOC variation corresponding to the considered working operation. Also in terms of power the proposed battery has a nominal power higher than the mean power of the load. Over cited loads introduced by hydraulic plant and KERS can be sustained by the large over-current capacity of the cells, which is also aligned to the capability of the other components, such as PM machine and drive.

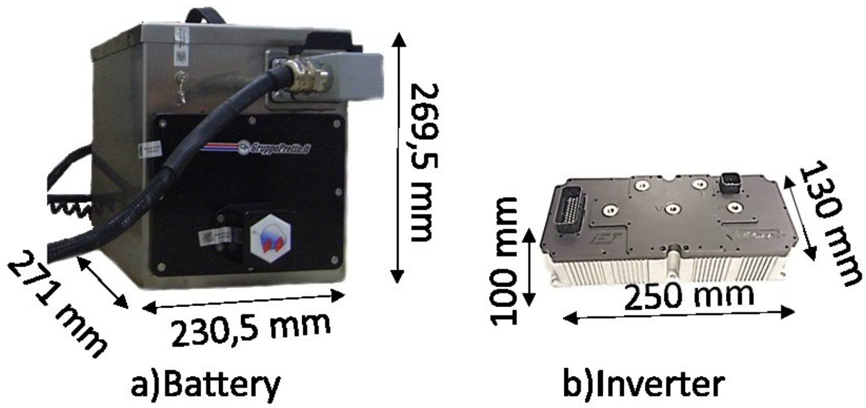

Figure 26: Adopted Battery Pack, Main encumbrances of the ~~accumulator~~ storage system (a) compared with the ~~controller~~ inverter of the electrical machine ~~of the motor~~ (b)

Table III: Main features of the proposed energy storage system

Feature	Value/description
Cell Type	Li-PO Kokam SLP B12021626
Number of.cells	14 (series connected)
Min./Nom./Max battery Voltage	42/51.8/58.1 V
Size	53Ah
Nominal energy	2.75 kWh
Protection	IP 66
Max Current (5C)/max power	250-270 A/ 13-14 kW

D. Preliminary simulation results of a typical mission profile

In order to verify the preliminary sizing of the KERS and in particular of the storage system, authors performed a complete simulation of the recorded mission profile visible in Figure 3~~Figure 3~~.

In particular simulation was performed adopting the complete model of hydraulic plant (visible in Figure 16~~Figure 16~~) to calculate the energy consumptions associated to lifting and manipulation of dumpsters. Number of manipulated dumpsters and performed operations during a mission are available from recoded data. Calculated energy consumptions are assumed as auxiliary loads imposed to the accumulator when the vehicle is stopped and the ICE is switched off. This loads are then imposed as inputs to the vehicle model equipped with the selected powertrain configuration (i.e. including the KERS system) also simulating vehicle speed profiles referred to the same recorded mission. As a consequence, it is possible to correctly evaluate all the energy flows, from hydraulic to the on-board electrical system. Particularly, energy flows from and to the electrochemical storage system, taking into account regenerative braking.

In this way it was possible to calculate, as example the behaviour of the energy storage system in terms of SOC considering different levels of maximum regenerative braking torque starting from the maximum intermittent torque of the adopted PM machine (49 Nm for 60 s) to the continuous one (a continuous torque of 16.5 Nm). in particular, in Figure 27~~Figure 27~~, it is considered the case of vehicles that starts their service with an initial value of the battery SOC equal to 100%.

An initial SOC value of 100% should be justified, as example, by the availability at vehicle depot of an external source to recharge the electrochemical storage system during the night.

Since the system is tuned to maintain the battery between 15 and 95% of SOC, in approximately the first hour of service the state of charge of the battery drop from 100% to 95%; once this transient it’s terminated in almost every configuration the system is able to perform the assigned mission finishing the mission with a 95% of SOC which assure that the vehicle should be reused the next days without need of any additional recharge of the battery.

Looking at simulation results of Figure 27~~Figure 27~~, it should be recognize the importance of one realistic mission profile from experimental measurements:

- Battery discharge depends on the number of carried dumpsters; in a town like Livorno there are important sites like central markets, harbour docks, industrial areas, in which several dumpsters are grouped together. These sites are the most demanding for the system since higher battery consumptions are involved at a single stop (or in stops which are quite near with limited possibility of recharge).
- In order to avoid an excessive chatter of the regulator around the 95% of SOC, the regulator is implemented with a hysteresis corresponding to about 2% of estimated SOC. As a consequence, there are some particular conditions in which the SOC threshold of 95% is exceeded (braking manoeuvres starting with a SOC of about 95%).

Higher values of regenerated braking torque involve lower fluctuations of the SOC of the energy storage but higher thermal stress for the PM motor which is much more overloaded. However also in this sense simulations of the thermal behaviour of the motor-drive systems performed according (5)~~(5)~~ assure a good thermal balance of the motor and power electronics. It's also interesting to notice that three performed simulations differ each other in terms of electric braking torque or regenerated power of about 300%. As a consequence, the system is able to perform the assigned mission profiles even considering a wide variation of motor performances. This is a clear demonstration of robustness of the proposed calculations respect to component tolerances and to uncertainties which makes the author confident respect to the final calibration and validation of the complete system.

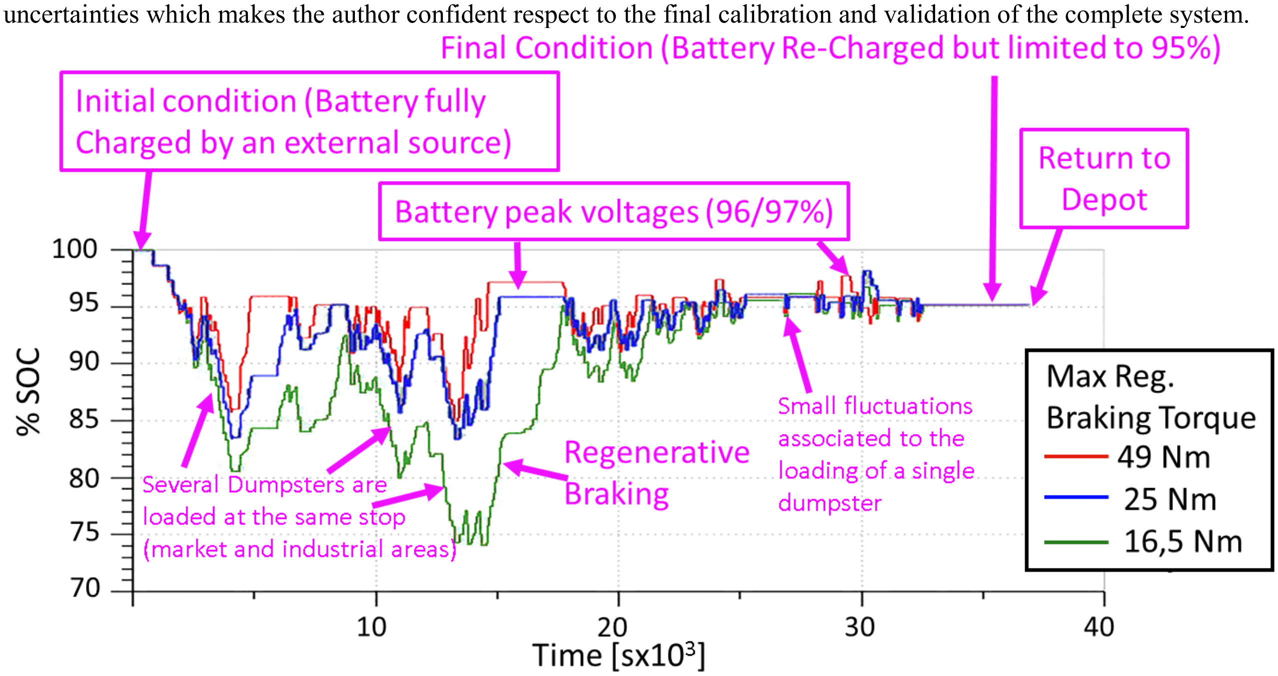

Figure 27: SOC behaviour considering different levels of maximum regenerative braking torque (initial state of accumulator corresponding to fully charged)

The same simulation scenario corresponding to the mission profile of Figure 3~~Figure 3~~ was then repeated considering a very low initial value of the state of charge of the battery, around 10%. This is a simulation scenario involving unusual conditions for the storage system, since the system is tuned to keep the battery SOC at a level higher than 15%. It should be also noticed that it's a good practice to have the availability at the vehicle depot of an external power source to recharge batteries. In particular, very low SOC values should be caused, as example, by prolonged periods of inactivity of the vehicle, by aging or by abnormal mission profiles. So this should not be considered as a normal working conditions but a worst case scenario to which the proposed systems has to survive assuring the end of the assigned mission profile. Corresponding simulation results in terms of battery SOC are shown in Figure 28~~Figure 28~~: independently from the imposed level of braking torque the system is able to perform the desired mission profile ending the mission with a satisfactory level of battery SOC which assure for the following day easier operating conditions. However, in the simulation scenario corresponding to the application of the lowest regenerative braking torque, the level of SOC remain around or below 15% for a duration corresponding of about 30-35% of the total mission time. This working behaviour is not desirable since it involves that a large part of the energy is not recovered in the braking phase but directly generated by the PM machine during a traction manoeuvre in order to keep the battery SOC around a minimum acceptable level (15%). From simulation results it should be deduced that it is possible to start experimental testing of the proposed system considering a level of braking regenerative torque of 49 Nm, being feasible a reduction to a level of about 25 Nm for a more cautious design in terms of thermal overload. Lower regenerative torque corresponding to the continuous performance of the motor (16Nm) should be adopted only tolerating a lower system efficiency in case of extremely degraded conditions.

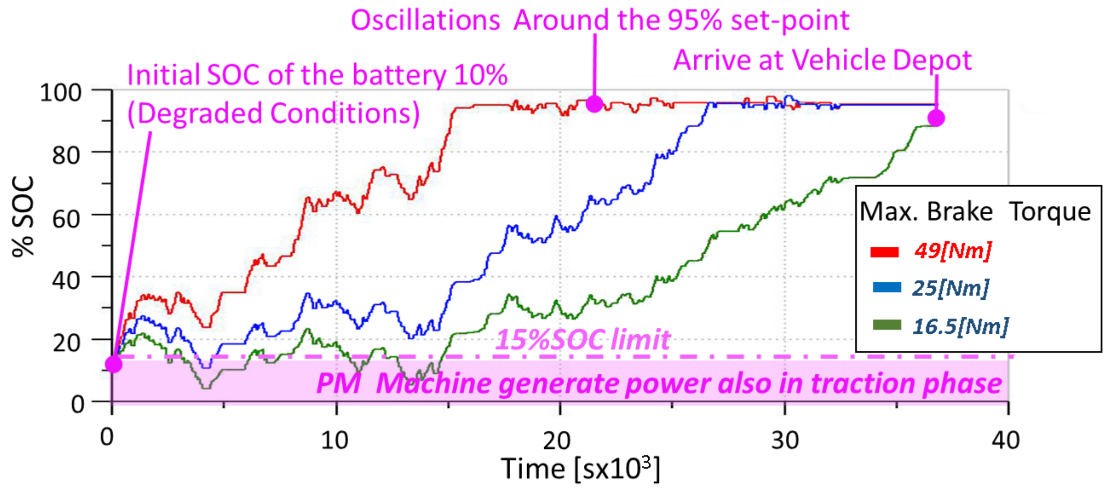

Figure 28: SOC behaviour considering different levels of maximum regenerative braking torque (initial state of battery corresponding to 10% of SOC)

From simulation results it i~~'~~s possible to calculate peak and mean regenerated electric power during a braking phase, which are respectively 9800 W and about 4600 W. These values are calculated considering braking manoeuvres from 50 km/h and the maximum braking performances of the PM motor (49Nm). Considering specifications described in Table III~~Table III~~, these peaks of regenerated power can be tolerated by the chosen storage system ~~accumulators~~, since the peak power of the battery is about 14 kW. Also the typical duration of a stop braking is 20-40 seconds, and the system is automatically protected against prolonged braking manoeuvres lasting more than 60 seconds.
Regarding the hydraulic plant, peak and mean values of consumed power are quantified respectively in 5000 W and 2500 W. Mean consumed power involves low currents which are compatible with the nominal behaviour of the ~~accumulators~~storage system. Also peak power ~~requirements~~ solicitations are ~~tolerable~~ compatible with respect to the maximum performance~~s~~ of the ~~batteries~~ battery, ~~both~~ in terms of amplitude and duration.

E. Preliminary Cost Evaluation

Considering the logged mission profile of Figure 3~~Figure 3~~, it is possible to quantify fuel saving v_{save} which can be obtained with the installation of the proposed system.
In the current version, the proposed system has almost no influence on fuel consumptions of the ICE (Internal Combustion Engine) when the vehicle is moving, especially if the SOC of the battery is higher than 15%. In fact in this conditions the hydraulic plant is not working and the pump is disconnected thanks to the freewheel hub visible in the scheme of Figure 5~~Figure 5~~.
As shown by previous simulations, visible in Figure 27~~Figure 27~~ and in Figure 28~~Figure 28~~, a SOC under 15% is an improbable condition. As a consequence, when the vehicle is moving, the system is used only to perform regenerative braking. Recovered energy is used to feed the hydraulic plant when the vehicle is stopped.
The amount of fuel that should be saved by adopting the proposed system should be calculated considering the energy consumption to feed the hydraulic plant, keeping the internal combustion engine rotating at a constant speed of 1000 rpm as in the conventional plant.
This evaluation was performed according (7)~~(7)~~ by integrating the power consumption of the hydraulic plant W considering efficiency of vehicle engine η_m and specific energy of the fuel k_w:

$$v_{save} = \frac{1}{k_W} \int \frac{W}{\eta_m} dt \qquad (7)$$

Calculation performed according (7)~~(7)~~ are affected by heavy uncertainties especially in terms of engine efficiency η_m since the amount of power W that the vehicle engine has to generate (few kW) is quite small respect to max performances of the internal combustion engine at its nominal speed (about 110 kW) as visible in Figure 18~~Figure 18~~.
In this operating conditions the estimated efficiency of the motor is a quite uncertain parameter even respect to efficiency maps of the ICE which is visible in Figure 29~~Figure 29~~: typical operating conditions of the ICE when it is connected to the conventional hydraulic plant corresponds to an operating speed a of 1000 rpm and values of equivalent engine throttle, which are near to minimum values (0.15-0.2) since for lower values the motor is not capable to self-sustain its motion at the assigned speed. For a comparison similar data referred to motors with the same size are also available in literature, as example in [36]~~[33]~~.

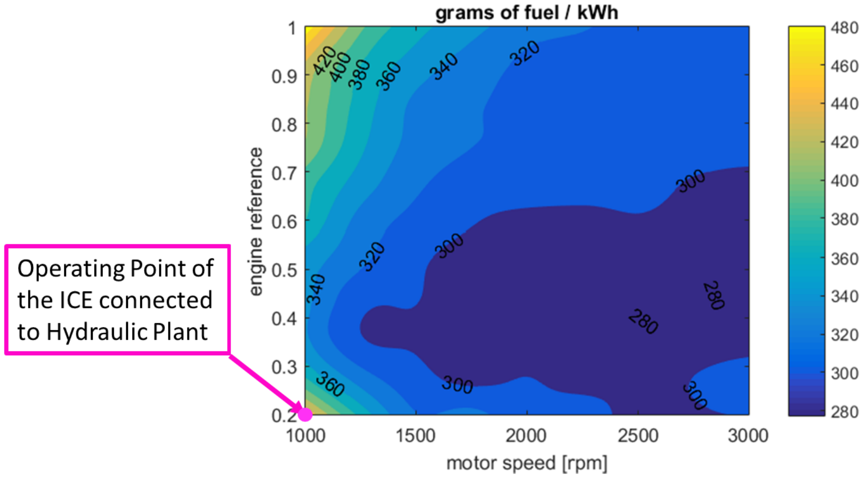

Figure 29: efficiency of the ICE (Internal Combustion Engine) as function of motor speed and equivalent engine throttle/reference

Extrapolated/uncertain values of the considered working conditions should involve very poor performances corresponding to about 450 g/kWh of delivered power. The typical power consumption of the conventional oil plant corresponds to a power demand of about 5 kW. For this reason, for every hour in which the vehicle is stopped feeding the hydraulic plant more than two kg of fuel are consumed (2250g). Considering a mean density of the fuel [39]~~[36]~~ and the current price of fuel in Italy (about 1.3 Euros/litre), it's possible to evaluate the equivalent cost of the fuel that should be saved by adopting the new proposed solution (3.5 euros/hour of service of the hydraulic plant).

According the experimental mission profile of a vehicle in the city of Livorno, the vehicle is stopped and the hydraulic plant is working for about a fifth of the total mission time (about two hours on a total mission time of about ten hours)

Mean fuel saving per hour S_m should be calculated as the time weighted mean (8)~~(8)~~of the saving during vehicle motion S_v and during the operations performed by the hydraulic plant S_h

$$S_m = S_h \frac{t_h}{t_{tot}} + S_v \frac{t_{tot} - t_h}{t_{tot}} \approx 0.2 S_h \approx 0.7 \frac{€}{h} \qquad (8)$$

Where in (8)~~(8)~~ t_{tot} is the total duration of the mission and t_h the one in which the vehicle is stopped and the hydraulic plant is operating.

For these reasons authors expect appreciable savings corresponding to 0.5-1€ (0.7 considering the above described calculations) for each hour of service but this calculation has to be confirmed when specific measurements performed with the equipment described in Figure 19~~Figure 19~~ should be available.

Authors are aware that these calculations concerning the foreseen fuel savings are currently not supported by a direct validation with experimental tests on the vehicle, but on the other hand performed direct and indirect validation activities should assure an acceptable level of accuracy of performed calculations for the following reasons:

- Hydraulic Model of the servo-plant is completely validated: energy savings are evaluated considering the power that have to be produced to feed this plant.
- Mission profile has been recorded so there is a quite reduced uncertainty in terms of operating scenario.
- Simulations have been carried on considering different settings of the KERS in which recovered power during a brake is varied of 300%. In all the simulated scenarios the system performed well; even considering tolerances on real components, authors are quite confident that with a safety margin of 300% it should be quite easy to calibrate the system in a real operating condition.

This estimated fuel saving should be further refined also considering the impact of engine restarts which typically causes slight increase of fuel consumptions as studied by many works in literature, as example of Canova [37]~~[34]~~,[38]~~[35]~~. In this preliminary phase of the design this aspect has been neglected but it should be better investigated when it will be possible to perform further experimental activities on a fleet of prototypes. Additional electric power consumptions, not considered in these preliminary simulations should be tolerated considering large design tolerance~~s~~ of the proposed KERS system: in this case~~-~~, an increase of the regenerated electrical power, although ~~should reduce~~reducing the reliability margin of the system, ~~but it~~ should also increase the amount of saved energy, increasing the profitability in terms of saved fuel.

The overall cost of the first prototype of the proposed system should be estimated between 6000 and 7000€ (depending on the production scale), considering a cost of about 3000€ for batteries and another 3000-4000€ for the other components (motor, drives and clutch). Also this preliminary evaluation is quite approximated since it's referred to the cost of the components for a single prototype.

Considering at least 4000 hour of service each year, it should be concluded that after 2-3 years the initial investment should be counterbalanced by the revenue of fuel saving.

Considering the reduced break even time this kind of solution should be recommended not only for new installations but also as kind of retrofit kit that should be used to revamp existing vehicles even with an appreciable service life.
Author are also convinced that for the evaluation of the profitability of the proposed system also other non-secondary aspects have to be considered:

- Reduction of Pollution: expected fuel saving should also involve an appreciable reduction in terms of pollution.
- Reduction of Noise: electro-hydraulic manipulation of dumpsters produces less noise respect to conventional one (vehicle engine is switched off).
- Proposed Pump Controlled Plant involve also an improvement of performances of the installed hydraulic servo-system.
- Weight and Encumbrances: estimated weigh of the proposed solutions including hydraulic pump, pump, motor, drive and batteries is less than 50kg. However, it should be considered that new pump is used as a substitute of an original bigger one and that the circulating oil flow is about a half respect to the original solution. As a consequence, it's expected a weight reduction in terms of oil stored in the oil tank of at least 30 kg. Encumbrances of different components are described respectively in Figure 8~~Figure 8~~ and in Figure 26~~Figure 26~~. As a consequence, the impact of the system in terms of weight is negligible. Also encumbrances are not too big considering that different components such as batteries and drive should be allocated in a different position respect to the motor.

Currently, the industrial partner of this activity, Pretto Group SRL is implementing the proposed system on a wide variety of different trucks (about one hundred) that should be used by several public administrations of the northern Italy. As visible in Figure 30~~Figure 30~~, the system is currently composed by the components described in this work. However, the way adopted to constraint the proposed system to the vehicle has to be customized according different chassis and different on board equipment. Authors are confident that experimental data from real operating conditions should provide a further validation of the work presented in this paper. However, considering the rapid response of the market, authors has at least completed the first aim of this activity: the development of an innovative and successful industrial product.

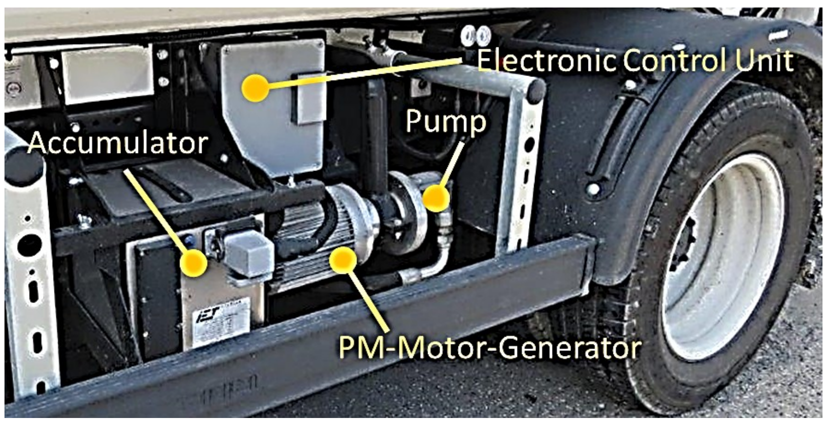

Figure 30: the proposed system assembled on a real truck

6. Conclusion

An innovative layout for servo-hydraulic vehicle systems fed by a KERS has been presented in this work.
In particular authors have focused their attention on a common application like garbage collection demonstrating the feasibility of the proposed solution on a benchmark vehicle. Thanks to the results of this research activity, Pretto Group, the industrial partner that have supported this work, have started the installation of the proposed solution on a fleet of industrial trucks for garbage collection, so authors are confident that further results and feedbacks should be available in the next months.
It should be recognized that the proposed solution should be extended for many different applications with the following specifications:

- mission profiles involving frequent accelerations and decelerations (needed to exploit a KERS)
- on board servo-hydraulics systems that have to be frequently activated using a quantity of energy that can be recovered with regenerative braking of the vehicle.

In particular, some possible extensions of the proposed solution to the following applications should be considered:

- Vehicles performing collection and manipulation tasks with hydraulic servo-systems;
- Vehicles equipped with hydraulics servo-systems used for inspection or maintenance;
- On board servo-systems designed to automate docking and transfer operation of goods;
- On board servo-system devoted to assist the access of people to public transport system.

In a medium-long term scenario pure full electric or hybrid vehicles should represent the ideal solution for urban services like garbage collection.

However, in this work authors have demonstrated that with affordable investments and limited technical intervention it's possible to introduce important improvements in terms of efficiency, environmental impact also on conventional or existing fleets of industrial vehicles. It should be noticed that most of the performed modifications performed on the vehicle and in particular on the electro-hydraulic plant are the same that have to be performed for a full hybridization of the system so this work should be considered also a contribution in that final direction.

7. Future Developments

An immediate development should be represented by the construction and the experimental testing of a full operating prototype on which experimental activities mainly concerning model validation and system calibration is performed. Since the installation of the proposed system has started on a first production of about a hundred of vehicles, authors are confident that further experimental data should be also available from the monitoring of this first generation of the product.

In parallel, the development of a pure electric or full hybrid solution that should be the object of a future work, has been started.

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