Systematic development of series-hybrid bus through modelling

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Abstract—**With increasingly stringent regulations on fuel emissions, vehicle manufacturers have started developing hybrid and electric versions of their vehicles. This paper presents a systematic approach to developing series-hybrid version of an existing bus through power-train modelling. The approach involves accurate modelling of the conventional bus, validating it by matching the simulation results with the tests conducted on the actual bus, and then developing the hybrid version of the bus.**

Keywords—***hybrid vehicle, modelling, powertrains***

I. Nomenclature

AUX	Auxiliary electrical load
BSFC	Brake Specific Fuel Consumption
ED	Electric Drive
EGS	Electrical Generating System
EM	Electric machine (either operating as motor or generator)
EPC	Electronic Power Conditioner
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
PMM	Power Management Module
RESS	Rechargeable Energy Storage System
SORT	Standardised On-Road Test

II. Introduction

With growing concern for environmental problems amongst governments and international policy formulation agencies, more stringent standards for fuel consumption and emissions have been developed. Vehicle manufacturers have focused their attention on development of hybrid and electric versions of their vehicles. These vehicles have advanced power-trains for efficient utilisation of energy.

Electric vehicles (EVs) appear to be the best way out as they imply reduced oil consumption and zero *in situ* emissions. However, factors such as high initial cost, short driving range, and long charging time are major limitations. Hybrid electric vehicles (HEVs) were developed to overcome the limitations of internal combustion engine (ICE) vehicles and EVs. An HEV combines a conventional propulsion system with an energy storage system and an electric drive. When driven in the electric mode, HEVs are zero emission vehicles (ZEVs). HEVs have an improved fuel economy, compared to conventional ICE vehicles, and have a longer driving range than EVs. Hybrid electric systems are broadly classified as series or parallel hybrid systems. In the series hybrid system all the torque required for propulsion is provided by an electric motor, while in the parallel hybrid system, the torque obtained from the ICE is mechanically coupled to the torque from the electric motor [1], [2], [3]. The series HEV solution is commonly chosen for hybridising buses [4], because of the inherent characteristics of this power train scheme, and will be pursued in this paper also.

This paper presents a systematic development of a complete line of series-hybrid and electric versions of existing city buses for the Italian bus manufacturer, Breda Menarini Bus (BMB) [5], through modelling. The models were made both using a commercial software, LMS Imagine.Lab AMESim® [6] (AMESim), and a custom-built package using Matlab Simulink™ [7] (Matlab). AMESim stands for Advanced Modelling Environment for performing SIMulations of engineering systems.

To inspire confidence in the quality of the models, first the existing bus was modelled and validated by matching the simulation results with the results on actual tests conducted on the existing bus. After confirming the parameters, models were developed for the series-hybrid versions of the bus. These were simulated on duty cycles of the cities where the buses are planned to be deployed. In Section III, the model for the existing bus and its validation is presented. Section IV presents the model for the series-hybrid bus. Finally, in Sections V & VI, the results of the sizing and conclusion of the study are summarised.

III. Modelling & validation of existing buses

A. Model of existing buses

Some of the existing BMB buses modelled are shown in Table I. Figure 2 depicts the model of the existing bus made using AMESim. Sub-models were made for the ICE, the automatic gearbox and the auxiliary load. The output from the ICE is given to the automatic gearbox and the auxiliary load. The automatic gearbox drives the wheels, and the feedback from the wheels (i.e. the difference between the desired speed and the actual speed) guides the response of the driver based on the required duty cycle. The model was configurable for different types of buses having different auxiliary loads and running on different duty cycles.

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TABLE I. SOME BMB VEHICLES MODELLED

	Bus Models		
	Vivacity M	*Avancity L*	*Avancity S*
Length	9 meters	12 meters	18 meters
Weight (trial)	9,67 tonnes	14,35 tonnes	20,99 tonnes
Weight (full)	13,29 tonnes	17,08 tonnes	25,06 tonnes
Engine	Deutz	Deutz	MAN
Capacity	4,8 litres	7,2 litres	10,6 litres
Max Power	158 kW	213 kW	235 kW
Torque	800 Nm	1200 Nm	1600 Nm
Consumption SORT1 cycle (trial load)	44,65 litres/100 km	49,66 litres/100 km	63,49 litres/100 km

In order to evaluate the true benefits of the series-hybrid and electric buses (which were to be developed), we needed to benchmark them against the fuel efficiency of the existing buses based on a standard duty cycle. Fuel consumption values of the existing buses on the Standardised On-Road Test SORT1 (shown in Figure 1) cycle were provided by BMB.

These tests were carefully carried out by TÜV Italia [8] along with the manufacturer. The SORT cycles were developed by the International Association of Public Transport (UITP) Bus Committee [9] for buses running on heavy urban, easy urban and suburban circuits and are an indispensable reference point for bus transport when assessing energy choices and the effectiveness of any measure put in place.

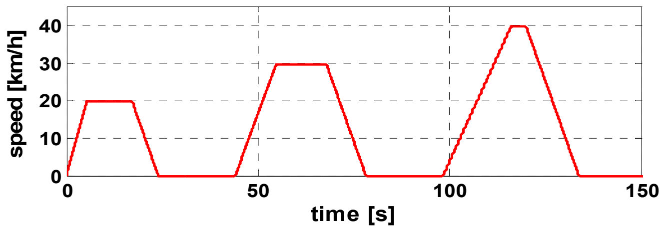

Fig. 1 The SORT1 standard cycle: speed profile

SORT provides realistic measurements as tests are carried out on-road and it applies to a bus and not a *single engine block* in a laboratory. Different buses can be compared using the same basic test method and protocol.

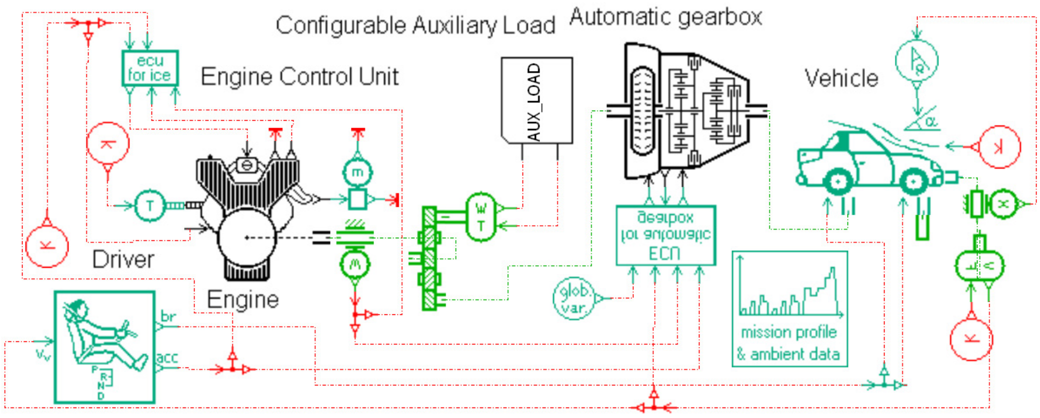

Fig. 2 The model of the existing bus on LMS Imagine.Lab AME Sim ®

B. Validating the model

BMB put at disposal of the study basic data about the bus, including some data on the engine and automatic gearbox. The buses employ diesel engines by major European automotive industries, while ZF is the automatic gearbox supplier. It also provided the actual duty cycles of its buses running in cities where the hybrid versions of its bus are planned to run. However, accurate data about the power absorbed by the auxiliary load was not available. The simulation results of the model were validated against the actual SORT1 cycle test results supplied by BMB. All the existing BMB urban buses were modelled and their simulation results compared with the test results given by BMB.

The notable feature of the model was its ability to succinctly and accurately reproduce all the results observed in the actual tests, including fuel consumption figures for the SORT1 cycle. Figure 3 shows the result of the power flow from the ICE to the wheels. A part of the power from the ICE is absorbed by the auxiliaries. The remaining power goes to the torque converter, then to the gearbox and finally to the wheels. The loss of power at each stage was clearly emulated by the simulation.

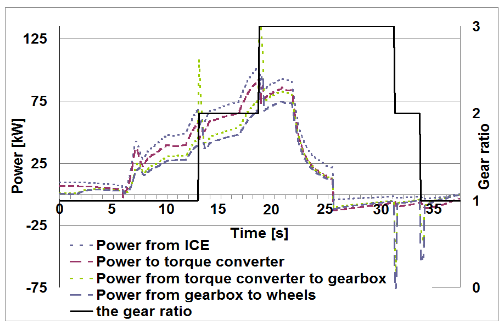

Fig. 3 The power flows in the model from the ICE to wheels through the torque converter and gearbox

It was noted that the simulations on the model matched these results to a very good degree, together with validation of the parameters used, including the fuel map. Once validated, the power requirement of the auxiliary load for each of the buses was accurately ascertained.

IV. Modelling the Series Hybrid Buses

The ICE of the conventional vehicle is sized for the maximum power and torque requirements since it is the only source to meet the power and torque requirements of the wheels. Apart from disadvantages like higher size, weight and cost, the ICE needs to operate at inefficient parts of the Brake Specific Fuel Consumption (BSFC) map, thereby consuming higher fuel. It would be more energy efficient, if the ICE operated only at the most efficient parts of the BSFC map. Secondly, conventional vehicles do not have the ability to recuperate braking energies. Instead, hybrid propulsion systems employ a Rechargeable Energy Storage System (RESS), which stores energy (either from braking or from the primary converter) that is later used for propulsion; and could employ an ON/OFF strategy [10] for the primary converter, which works to switch off the ICE when the vehicle is stationary (bus stops, traffic signals or jams etc), to enhance the comfort of the passengers by eliminating noise and pollutant emissions. In this paper, the authors employed the ON/OFF strategy.

A. The series hybrid propulsion architecture

The *series-hybrid* propulsion architecture adopted for this paper is shown in Figure 4, with the arrows along the power fluxes showing the actual directions when the numerical values are positive.

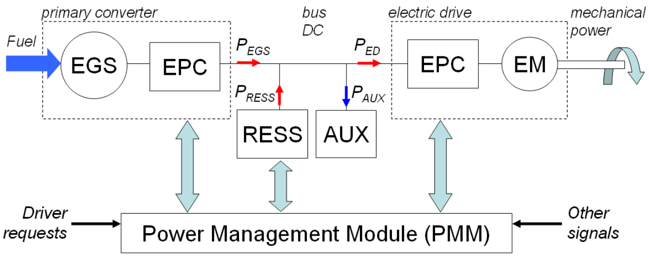

Fig. 4 Principle scheme of a series-hybrid vehicle drive-train

The ICE is coupled to an electrical generator (EGS). The presence of a storage system (RESS) provides the vehicle flexibility in sharing the power required for propulsion. This management is carried out by the on-board Power Management Module (PMM), which continuously monitors the load requirement and decides how to share the power amongst the two sources according to predefined goals (typical goal is vehicle efficiency maximization).

B. Sizing of components of the series hybrid propulsion system

An efficient series-hybrid electric propulsion system requires optimal sizing of all its components. Models of the series-hybrid bus were built on both AMESim and Matlab. The results of simulation were comparable, which gave the authors confidence in the quality of the modelling.

All subsystems were modelled weighting the accuracy and complexity for the purpose considered. In particular, since the fastest transients useful to globally size the hybrid drive train have constant times of the order of 100 ms, much faster phenomena, such as combustion dynamics or valve switching inside electronic converters, were considered to be algebraic. Figure 5 depicts the simulation scheme in AMESim. The main subsystems were:

- Internal combustion engine (ICE), the main source for the vehicle energy propulsion. The model for the ICE used the BSFC maps. The model could emulate the engine torque, mechanical power, engine efficiency, fuel consumption, emissions and engine speed.
- Electric generator (EGS) coupled to the ICE that generated electricity available for propulsion.
- Rechargeable energy storage system (RESS) that could be composed of devices such as electrochemical batteries, supercapacitors, fly-wheels etc. The authors modelled the RESS with a lithium ion battery, considering its good performance in terms of power density and energy density.
- Auxiliary electrical load (AUX) that could be lights, the control system, the air-conditioner etc;
- Electric Drive (ED), to provide power and torque to the wheels and also to produce regenerative power, consisting of an electric motor and a power controller; and
- The vehicle, which also contained sub-systems for mechanical transmission and vehicle dynamics. The final drive consisted of a fixed gear ratio driven by the traction motor. Mechanical equations describing the vehicle longitudinal behaviour was used.

Each sub-model was carefully constructed to be able to accurately emulate experimental results. e.g. the model for the electric motor/generator needed parameters in a file defining the lost power vs. the torque and the rotary velocity. The model of the battery needed data files listing the internal resistance vs. the depth of discharge. Similarly, the complete BSFC maps were fed to the ICE sub-model, and the model could determine the most efficient operating line, for the each level of power demanded. Efforts were made to model realistic sub-systems, building in parameters for efficiencies.

The PMM was the most critical element in the model. It was programmed to determine the most optimal way to meet the driver's requirements for power while utilizing the two energy sources of the vehicle. The authors employed the *forward approach* for this model, which was:

- a driving duty cycle (called *mission profile* in the program) fed to the driver block.
- the driver block converted the reference speed into commands for the PMM.
- the PMM determined the most optimal strategy based on the instantaneous power demand levels, and feedback from key parameters of the ICE, EGS, RESS and ED.

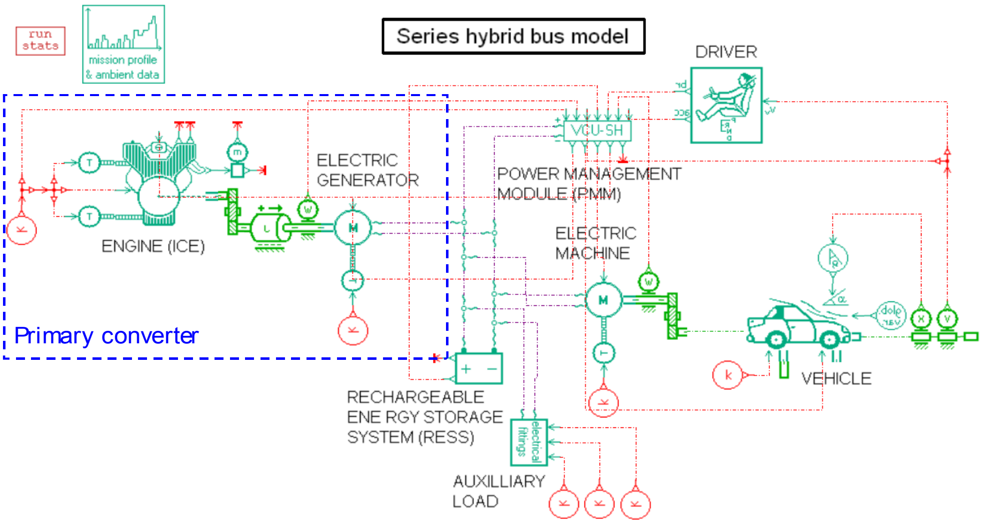

Fig. 5 Series-Hybrid bus model in AME Sim

C. *Possible energy management strategies*

In a series hybrid solution, all power for traction is electric. The sum of energies of the two (or more) power sources in the series-hybrid vehicle is usually depicted as a DC bus. Power needed for the traction and auxiliaries is taken from this DC bus.

The fundamental role of the PMM is to interpret driver's commands, and accordingly determine which part of the requested propulsive power would be delivered by the EGS and which by the RESS. In other words, to determine how to decompose the quantity P_{ED} (t) into P_{EGS} (t) and P_{RESS} (t):

$$P_{ED}(t) = P_{EGS}(t) + P_{RESS}(t) \tag{1}$$

This degree of freedom could be used to minimize an objective function that could be fuel consumption. The relationship (1) is guaranteed by the physics of drive train. A possible control strategy could be:

- $P_{ED}(t)$ is determined to answer the driver's commands as closely as possible. It could be considered a direct consequence of trip characteristics, vehicle mass and power losses in the ED.
- $P_{EGS}(t)$ is determined by PMM according to some optimization rule (that will be discussed later).
- $P_{RESS}(t)$ is automatically determined by difference.

The user load P_{ED} draws the main focus in this control strategy, while the power generation from fuel; P_{EGS}; is given a supporting role. This control strategy (described in detail in [11], [12]) is very often used in a hybrid vehicle, and is also adopted for this paper. The *useful* power that goes into the load $P_{ED}(t)$ could be imagined to be constituted by an average value and a ripple. Eq. (1) is thus modified as follows:

$$P_{ED}(t) = P_{EDa}(t) + r(t) \tag{2}$$

It is possible to control the system such that the quantity $r(t)$ is completely delivered by P_{RESS} (t), and does not form part of the primary converter:

$$P_{RESS}(t) = r(t),\ \therefore P_{EGS}(t) = P_{EDa}(t) \tag{3}$$

Hence, the ICE delivers only the average power requested by propulsion, leaving the RESS to deliver the rest.

The strategy presented above requires a consideration (even approximate), of the future system load, i.e. the future behaviour of the power demand P_{ED} (t), which is a function of the driver's request for torque and the vehicle duty cycle. The approximate level of power needed by the vehicle in future could be obtained by multiplying the past history of P_{ED} (t) with a simple filter, e.g:

- $P_{EGS}(t)$ is the output of a filter having as input $P_{ED}(t)$ and as a transfer function $1/(1+s\tau)$.
- $$P_{EGS}(t) = \frac{1}{T}\int_{t-T}^{t} P_{ED}(\tau)d\tau \tag{4}$$

In both cases a suitable value for τ needs to be chosen.

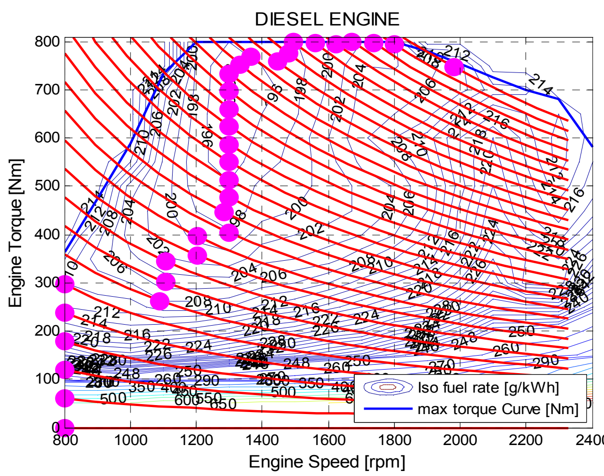

Fig. 6 Output of the internal optimisation algorithm: the optimal values of the ICE angular velocity are reported directly on the engine map

After determining $P_{EGS}(t)$, an internal algorithm was used to choose the optimal values of the ICE rotary velocity (Fig. 6), corresponding to the minimum fuel consumption. More details on possible hybrid vehicle energy management strategies can be found in [13] — [17].

V. RESULTS

The objective of the study was the sizing of a complete line of series-hybrid buses for BMB to augment their conventional buses. The propulsion system sizing was sized in accordance with the boundary conditions regarding performance of the vehicle at full load.

1. *Level road*

   a) max speed: 80 km/h

   b) pure electric mode on urban cycles (22% of the total time), as a zero emission vehicle (ZEV)

2. *Road with 16% gradient*

   a) max speed: 10 km/h (range 0,5 km)

   b) start-up acceleration: 0,3 m/s²

The RESS was sized considering condition 1b) (pure electric mode on level gradient), according to the specified range and maximum current limits for the Li-ion battery.

Conditions 2a) and 2b), respectively, identified the max tractive power and the max (starting) tractive effort for the propulsion system: therefore they completely defined characteristics for the ED.

The sizing of the ICE could be evaluated with reference to the *maximum power*, i.e., the max power needed by the ICE, or the *efficient power*, i.e., the power at which the engine efficiency is highest.

Due to the power management algorithms selected, the *efficient power* would also be the average useful power evaluated by considering the ON/OFF strategy for the primary converter. In fact, the two different sizing criteria could be summarised as:

- constant speed drive at 50 km/h, ICE always ON, fully loaded vehicle: the constant ICE power obtained is the *maximum power* required;
- Vehicle running the SORT1 cycle on level gradient with the ON/OFF strategy: when the vehicle is stationary or in ZEV mode the ICE is switched off. The ICE power was hence evaluated through the following energy balance equation:

$$P_{eff} = P_{avg} \frac{(t_2 - t_0)}{(t_1 - t_0)} \qquad (5)$$

where, P_{eff} is the efficient power generated from ICE during the ON-state, P_{avg} is the average power requested from the propulsion. E_{max} and E_{min} represent the switch ON-OFF limits (also indicated in Figure 7). The calculated power, P_{eff}, could be termed as *efficient power.*

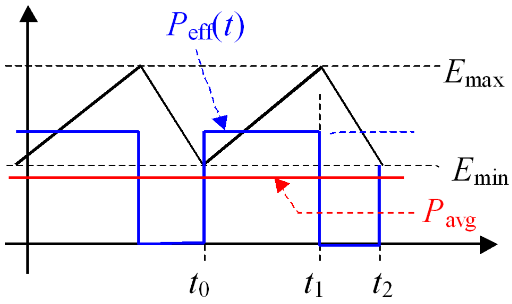

Fig. 7 Meaning of the quantities used for describing ICE ON-OFF strategy correction

The main characteristics of the sizing are listed in Table II.

TABLE II. SIZING OF THE CONSIDERED HYBRID BUSES

	Bus Models		
	Vivacity M	***Avancity L***	***Avancity S***
Length	9 meters	12 meters	18 meters
Weight (full load)	13,95 tonnes	17,96 tonnes	26,67 tonnes
Weight (partial load)	11,3 tonnes	14,3 tonnes	21,1 tonnes
Auxiliaries	6 kW	9 kW	12 kW
ICE max power	48 kW	61 kW	84 kW
ICE efficient power	36 kW	48 kW	69 kW
RESS Energy	31,1 kWh	38,9 kWh	51,8 kWh

From the main results it was interesting to note that the size of the ICE needed reduced significantly from the one in the conventional bus. The authors did not have access to specific fuel consumption maps for smaller engines, and hence, to evaluate the fuel consumptions, programmed the model to downscale the existing BSFC maps. The engine was downsized with reference to the torque, keeping the same BSFC values as the bigger engine for the smaller, thus avoiding, the poor efficiency zones of the original engine. Fuel consumptions are summarised in Table III, comparing performance of the hybrid buses to the conventional ones. This, however, was only an ad-hoc solution, but the authors are confident that the results obtained through this approach would also be similar.

TABLE III. FUEL CONSUMPTION

	Bus Models		
	Vivacity M	***Avancity L***	***Avancity S***
Length	9 meters	12 meters	18 meters
HEV (full load) SORT1 cycle	43,57 litres/100km	57,89 litres/100km	83,68 litres/100km
Conv.(full load) SORT1 cycle	55,98 litres/100km	75,89 litres/100km	111,71 litres/100km

Figure 8 shows the results of the simulation for the power fluxes (definitions of quantities in Figure 4) in the model for the *Avancity L* bus on the SORT1 cycle. It clearly shows the distribution of the power from the two sources. The RESS, ED, EGS, AUX power profiles are related by the following equation:

$$P_{ED}(t) + P_{AUX}(t) = P_{EGS}(t) + P_{RESS}(t) \qquad (6)$$

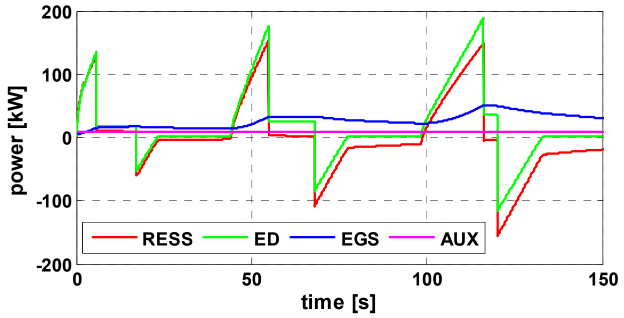

Fig. 8 Simulation of the Series-Hybrid Avancity L bus model on SORT1 cycle: power fluxes of the drive train

Similar such simulations were carried out for all the different bus models and on all the possible city driving cycles where the buses are finally targeted. Figure 9 and Figure 10 are related to the simulation on a real profile of urban cycle, measured by BMB during normal operation of buses in Bologna city.

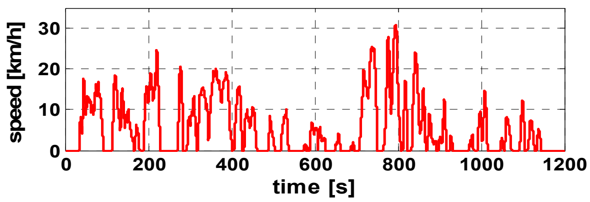

Fig. 9 Bologna1 cycle: speed profile

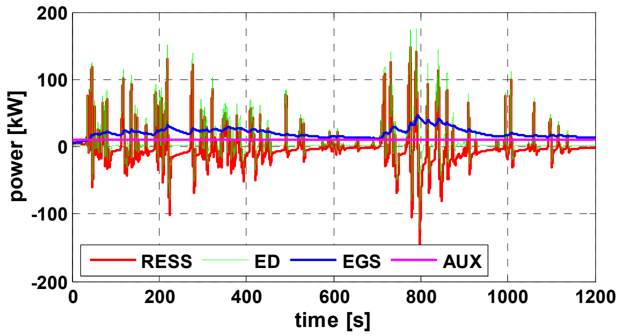

Fig. 10 Simulation of the Series-Hybrid Avancity L bus model on Bologna1 cycle: power fluxes of the drive train

VI. CONCLUSION

The paper presents the effort by the authors to develop a complete line of series-hybrid buses for the Italian manufacturer BMB to enhance their line of commercial buses. First, the existing buses were accurately modelled. The results of the simulation matched the results provided by the manufacturer of actual tests conducted on their buses. This gave the authors confidence in their modelling and they proceeded to model the series-hybrid models of the buses. These were then simulated for the different city cycles, and the different components of their hybrid propulsion systems were specifically sized and optimised.

The simulation results showed a significant reduction of over 20% in fuel consumption of the series-hybrid driveline compared to the conventional one, besides a reduction in the primary converter size. This confirms that series–hybrid technology is well-suited to the variable load requirements of urban buses.

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