Siemens ELFA Drive System for Hybrid Electric Vehicles

ABSTRACT

Concerned with fuel consumption and emissions, especially public transportation in urban areas, the ELFA electric drive system has been developed for hybrid bus applications. This modular system provides bus manufactures a cost effective solution with a maximum degree of design flexibility. The system is adaptable to buses with a wide variety of energy storage devices, power sources, and hybrid configurations. This paper introduces the characteristics of the ELFA hybrid system and presents performance results of buses which have been equipped with the system.

INTRODUCTION

As a result of increasing fuel prices, the operation of individual motor vehicles will become increasingly less economical, especially in urban areas. At the same time, in booming major cities with large populations, the desire to be mobile is increasing and the amount of traffic is continually on the rise despite a growing concern about pollution from road transportation sources. As a consequence, city buses are becoming more and more significant as a form of public transport.

In addition, government legislation on emissions and fuel economy is intended to substantially improve the air quality in cities through reduction in regulated pollutants. Battery powered electric vehicles (EV) promise a zero emission solution and help solve the energy crisis. However, public acceptance of EVs is limited by the high initial cost, short driving range, and long recharge time. Hydrogen fuel cell vehicles (FCV) have also been considered as an ideal candidate for future vehicles due to their high efficiency and near-zero emissions. However, a FCV is thought to be more of a far-term reality because of the high cost and low reliability, combined with the production, storage, and transportation challenges of hydrogen. Hybrid electric vehicle (HEV) utilizing an internal combustion engine offer a low cost, practical solution. They can reduce emissions and fuel consumption while overcoming the disadvantages of conventional vehicles, EVs and FCVs [1, 2].

As a result, the ELFA hybrid electric drive system has been developed. This modular system is adaptable to vehicles up to 18 meters in length and can be used with a wide variety of energy storage solutions (batteries or ultra-capacitors). Since the system is independent of hybrid types it can easily be adapted to FCV and EV variants when the challenges mentioned above have been overcome. With only minor modifications, the ELFA system can also be easily adapted for commercial service including delivery and refuse trucks. Vehicles fitted with the ELFA hybrid drive system have achieved significant improvements in fuel economy, lower emissions, and reduced service intervals.

The key components of the ELFA system are: electric traction motors (both induction and permanent magnet version are offered), IGBT based inverters, DCDC converters, generators, and the hybrid control module. This paper presents the characteristics of the ELFA hybrid drive system, and discusses the technical aspects as applied to different vehicle configurations. In addition, powertrain energy management and communication is briefly introduced and discussion of the in-house developed calibration and diagnostics tool is described. Finally, test results of a hybrid electric vehicle equipped with ELFA system are analyzed.

HYBRID ELECTRIC CITY BUS CONFIGURATION

A hybrid electric vehicle is one type of vehicle that combines a conventional internal combustion propulsion system with an electric propulsion system. HEVs can be further classified according to the way in which power is supplied to the powertrain: series, parallel, and power-split hybrids.
In a series hybrid, an engine output is first converted into electricity using a generator. The electricity can charge an energy storage device, supply power to a traction motor, or both simultaneously. Due to mechanical decoupling between the engine and the driven wheels, the engine can be operated in its most optimal region for maximum efficiency. The nearly ideal torque-speed characteristic of the electric motor makes multi-gear transmission unnecessary [3]. Other advantages of the series hybrid include its simple structure, ease of powertrain control, and flexible packaging.

The parallel hybrid allows both the engine and electric motor to deliver power directly to drive the wheels through a mechanical coupling. This eliminates the additional energy conversion step found in a series hybrid, but also forces the engine to operate in a wider speed band thus reducing its efficiency. Another disadvantage is that transmission is indispensable in order to adapt the output speed and torque of the engine to the wheels. This adds complexity to the system.

The power split configuration combines the features of both the series and parallel hybrids. It requires the use of an additional electric machine and a planetary unit which makes the drivetrain relatively more complicated and costly.

The driving profile of a city bus differs greatly from that of a passenger vehicle. The cycle is characterized by frequent start/stop operation (i.e. at bus stops, traffic lights, and heavy traffic), and low average speed. A typical inner city drive cycle consists of approximately one third of the time at zero speed, one third acceleration, and one third deceleration. Figure 1 shows the speed over the duration of the New York Manhattan Bus Cycle, which was developed based on actual observed driving patterns of urban transit buses in the Manhattan core of New York City. During this 1089 second driving cycle, the average speed is only 7 mph [4].

![Figure 1 – New York Manhattan Driving Cycle][4 Reprint]

The study indicates that the series hybrid configuration is the most suitable for medium and heavy duty commercial vehicles including buses, trucks, and military applications because of its simple structure, high efficiency, low emissions, simple control, low noise, passage comfort, and easy packaging [5]. Series hybrids are very similar in design to that of a zero emission vehicle (EV and FCV) and thus require little or no modification in the future when technology advances towards a zero emission solution. Additionally, series hybrid can recapture most, if not all, of the available regenerative braking energy, where as parallel hybrids are regen limited. Therefore, series hybrids are the preferred path to the ultimate goal of the city bus application: zero emission. For these reasons, there is a much greater penetration of series hybrid electric buses in the market today such as those offered by Ebus, Electric Vehicle International, BAÉ, Daimler, and ISE Research to name a few.

**ELFA HYBRID ELECTRIC DRIVE SYSTEM**

The research shows the series hybrid configuration is an appropriate fit for city bus transit applications [1, 5], and consequently the ELFA hybrid electric propulsion system are developed to satisfy the needs and requirements of this application. As mentioned, the system can be easily adapted for use with an EV or FCV. Because of its component modularity, the system can be adapted to almost every bus type and tailored to the specific requirement profile.
ELFA DRIVE SYSTEM HARDWARE

Electric motor

Electric motors play an instrumental role in the success of EVs, HEVs, and FCVs. There are two major types of motors suitable for these vehicle applications: induction and permanent magnet. Typical requirements for drive technology include: high torque density, high power density, wide speed range, high efficiency, high reliability, robustness, low maintenance, and low cost.

Unlike passenger vehicles, the length and weight of buses can vary greatly. A majority of city buses are 12 meters in length with a total weight of 16 to 18 tons. There are smaller buses at 9 meters long with a weight of 8 to 12 tons. Some shuttle buses such as those used for airport transit are even shorter and lighter. On the other end of the spectrum are double articulated buses at more than 18 meters in length. To meet these variants, a family of induction motors and PM machines has been developed. An induction motor (left) and a PM motor (right) are shown in Figure 2. The induction motors are liquid-cooled (water and glycol), 4-pole asynchronous machines with squirrel cage rotors. They are simple, robust, and can operate in a wide speed range. These motors are most commonly used as the propulsion drive motors. If one motor is not sufficient to meet the vehicle power request, two motors can be combined together with a summation gear. Alternatively, a larger motor or PM can also be utilized.

The PM motors are liquid cooled, synchronous machines with permanent magnet exited rotors. They possess unique characteristics (i.e. high efficiency, high torque, and high power density) because of the absence of rotor windings and associated rotor copper losses. However, PM motors inherently have a short constant power range as a result of the limited field weakening capability, resulting from the presence of the PM field [5]. The PM machine is more expensive than its induction counterpart due to the utilization of permanent magnet materials. These motors are most commonly used as generators or for high power requests such as 18 meter long bus applications. For this motor, a step-down gear unit is not required, which further improves the efficiency and eliminates the need for gearbox oil servicing.

The ELFA system offers over twenty different sizes of motors with continuous power ratings from 60 kW to 260 kW. Most motors are operated at 650 V voltage, but a few can be powered with 300 V to match the voltage level determined by bus OEMs. All of the motors have carry IP65 protection ratings. The motors are designed for environmental temperatures from -30C to +70C and altitudes up to 2500 meters above sea level.

As an example, the 85 kW induction motor shown in Figure 2 has the dimensions (LxWxH) of 510x245x245 mm and weighs of 120 kg. The size of the 260 kW PM motor in the same figure is 660x510x500 (LxWxH) mm and weighs 500 kg. The volume of the PM motor is less than 2 times of the induction motor but has 3 times the power rating and 4 times the weight. This comparison indicates that the overall weight and volume has been significantly reduced which leads to a much higher power density.

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Figure 3 shows an induction motor torque and power curves. Although the rated power is 67 kW continuous, the maximum power of the motor can reach 120 kW. The motor can produce up to 430 Nm of torque at low speed. The shape of the motor torque curve is similar to the curve generated by an engine with a transmission. These characteristics allow excellent utilization of the electric motor for operating a vehicle at low speeds, improving acceleration, and capturing energy by acting as a generator when the vehicle is slowing down.
Unlike traction motors, the generators are all PM machines designed to provide high efficiency power conversion from the engine to the energy storage device. The speed range of the generators is much lower than that of the traction motors so they can be directly mated to an internal combustion engine without a gearbox. Figure 4 shows the maximum power and torque curves of a 90 kW generator which has a long constant torque range. It also shows the generator efficiencies at its maximum torque. The efficiency varies from 80% to 94% depending on the operating speed. It is much higher than engine efficiency and also higher than its induction motor counterpart which has the maximum of 90%. The dimensions of the PM generators are very similar to that of the traction motors. As a consequence, vehicle manufacturers can essentially keep their chassis design exactly the same when converting to hybrid technology since the generator unit can be installed in the space previously occupied by the automatic gearbox. PM motors can also be used as direct drive units, providing additional efficiency in the lower speed range of operation. The use of PM motors allows the elimination of the step-down gear unit, delivering better fuel consumption and reduced operating costs.

**Figure 3 – Induction Motor Torque and Power vs. Speed**

**Figure 4 – PM Generator Torque, Power and Efficiency Curves vs. Speed**

**Power Electronics**

The power electronic circuits used in the ELFA system include rectifiers, inverters, and DCDC converters. They provide the functional connection between the DC link voltage and the variable speed electronic motor and generator. The power electronics play a key role in the traction system as they control the motors, generators, and auxiliary drive system. The power electronics offer an impressive 6K9K degree of environmental protection and can be operated from either 12 V or 24 V input. Technical advances have provided improved efficiency and reliability for these components and have helped make electrical traction power feasible for vehicle applications.
Figure 5 shows the block diagram of the ELFA inverter as a 4 phase system. Each phase comprises two IGBTs (Insulated Gate Bipolar Transistors) with total of eight identical IGBT modules. The DC link voltage consists of capacitors and continuous discharge resistors. The tasks of DC link include stabilizing the DC voltage, absorbing AC current components, supplying reactive power, buffering regenerative energy, balancing voltage distribution, and discharging during power down. Table 1 shows the characteristics of the inverter.

Table 1 – Inverter Characteristics

<table>
<thead>
<tr>
<th>Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated DC Voltage</td>
<td>650 V</td>
</tr>
<tr>
<td>Operating DC Voltage</td>
<td>300 – 700 V</td>
</tr>
<tr>
<td>Rated Current</td>
<td>250 A</td>
</tr>
<tr>
<td>Rated Power @ 650 V</td>
<td>200 kW</td>
</tr>
<tr>
<td>Max. Current (10 s)</td>
<td>350 A</td>
</tr>
<tr>
<td>Dimension (L x W x H)</td>
<td>411 x 454 x 183 mm</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>-25°C to 50°C</td>
</tr>
<tr>
<td>Max. Switching Frequency</td>
<td>10 kHz</td>
</tr>
<tr>
<td>Cooling Media</td>
<td>Water Glycol</td>
</tr>
<tr>
<td>Weight</td>
<td>30 kg</td>
</tr>
</tbody>
</table>

For typical applications, the electric motor is connected to three phases of the circuits L1, L2, and L3, shown in Figure 5. The control software can operate the electric machine as either a motor or a generator. When it is running as a motor, the function of the inverter is to convert DC voltage of the energy source (battery, ultra-capacitor, or fuel cell) to 3 phase AC voltage. The output of the inverter is controlled by means of a pulse-width-modulated (PWM) signal to produce sinusoidal waveforms. Certain harmonics exist in such a switching scheme, but high switching frequency is used to move the harmonics away from the fundamental frequency [6]. During braking, the electric machine is controlled to achieve regenerative braking and runs as a generator. The inverter is operated as a rectifier which converts the AC voltage produced by generator back to DC voltage and charges the batteries or ultra-capacitors. For cost-effective reasons, the inverter was not designed to match the most powerful motor. Rather, if one inverter is not capable of offering enough output power to a motor, two inverters can be connected in parallel to meet the requirement.

The fourth phase of the inverter offers large design freedom to the vehicle OEMs. It can be connected with a wide variety of different devices depending on the system design. Alternatively, when the voltage of the energy storage is lower than the system voltage (or needs to control a fluctuating voltages in the case of an ultra-capacitor or fuel cell), a DCDC converter is used to boost the DC link voltage. The ELFA system includes inductors which can be connected to the 4th phase to make up the bidirectional DCDC converter. Figure 5 shows the inductance box (in gray) and its connection to the inverter. In the boost operation mode of the converter, the
power is transferred from the energy storage system to the DC link. In buck operation, the power flow is reversed. A lower voltage energy storage device, such as a battery or fuel cell, typically results in a lower cost for that component. This also helps reduce the weight and required packaging space. This is another example of the design flexibility the ELFA system offers.

Braking resistors can be connected to the fourth phase of the inverter and controlled by switching the IGBT ON and OFF. During regenerative braking, the resistors are utilized when the batteries or ultra-capacitors can no longer absorb energy. The excess energy is then dissipated into the braking resistors to provide a consistent driving feel to the drive and to ensure vehicle safety. The ELFA system supplies 60 kW, water-cooled braking resistors to serve as an auxiliary brake. The resistor turn the kinetic energy into heat that is discharged via the braking resistor water cooling system which is most commonly connected to the combustion engine cooling circuit. The use of braking resistors also reduces the wear of the conventional mechanical brake and thus decreases the cost and maintenance effort.

In addition to generators and traction motors, the ELFA system can also provide an auxiliary motor solution. The auxiliary motor can drive power steering units, air compressors, etc. The auxiliary motor allows an OEM to remove parasitic loads from the internal combustion engine, thus improving the overall efficiency of the system. For FCVs and EVs, the auxiliary motor must be implemented.

**ELFA DRIVE SYSTEM CONTROL AND SOFTWARE**

A series hybrid electric vehicle is an integrated system that comprises many sub-systems including the engine/generator, electric drive, energy storage, chassis control, fuel delivery system, etc. Each is also a complex system that has its own functionalities and desired performance. Consequently, these sub-systems must be coordinated in an optimal manner to achieve different objectives including fuel economy, emission reduction, and vehicle performance. With the increasing complexity of the powertrain system and the need to achieve multiple objectives, an integrated vehicle-level controller is often required to accomplish this tasks [7]. To reduce the development time for bus OEMs, a drive system controller (DICO) for each system will be provided together.

**Control Architecture**

The control architecture of the ELFA drive system is shown in Figure 6 (note: this architecture will vary depending on the application). The communication of the DICO to the various electronic units of the vehicle is done via the Controller Area Network (CAN) bus. The DICO works not only as a gateway between the controllers of ELFA drive system and the electronic units of the vehicle, but also as a supervisory powertrain controller that controls the operation of the hybrid system, monitors the system status, and manages communications. It can communicate with the Engine Control Unit (ECU), braking system (i.e. ABS and traction control unit), Electronic Vehicle Control Unit (EVCU), and energy storage management unit. These units are normally provided by bus manufactures or suppliers and transfer data to the DICO via the standard SAE J1939 protocol. Custom protocols are also supported.

![Figure 6 Control Architecture of a Hybrid Electric Vehicle](image)

Based on the drive input (accel pedal, brake pedal, etc) as well as the state of other components, the DICO determines the desired outputs to be generated such as motor speed and engine torque. These desired output signals are sent to the corresponding controllers (e.g. ECU, EVCU, ELFA inverter, etc) and become the commands for these units.
The functions of the different inverters of the ELFA system, shown in Figure 6, are the control of the drive motor, the generator, the fuel cell (not included in the figure), auxiliary, and the DCDC converter. In order to achieve the functionality, the inverters receive the messages from DICO through the internally developed CAN bus protocol and perform consequent actions with assigned machine.

To increase the ELFA system efficiency, variable frequency drive (VFD) technology is applied to motor control. The inverter regulates the power to the motor, supplying variable frequency variable amplitude AC to the motor. To support a dynamic system control of the powertrain, the inverters provide feedback messages to DICO on the proprietary CAN bus. This design offers broad flexibility, supporting different hybrid categories (HEV, FCV, and EV) and keeps the ELFA system standardized.

**Control Strategy**

Improvements in both fuel economy and emissions of a HEV strongly depend on its powertrain control strategy. The ELFA hybrid system considers two components in a vehicle:

- Power Source (PS), which generates power. This can be a generator driven by an engine or a fuel cell;
- Energy Source (ES), which is capable of storing energy and could be battery or ultra-capacitor.

The control strategy needs must determine the power distribution between the PS and ES, so that the power requirements and other constraints are satisfied. The main objective of the controller is to meet the power demand commanded by the driver, while at the same time maintain the ES state-of-charge (SOC). To achieve the above objectives, many kinds of control strategies for series HEVs have been proposed and developed. Some strategies such as global optimization can not be used in practice because of the request for a prior knowledge of future driving conditions. Roughly the strategies applied in real-time can be categorized types: thermostat control method (ON/OFF)\[8\], power follower strategy [9, 10], and power split and minimization of equivalent fuel consumption control strategy [11, 12].

The ELFA system has its own fully developed strategy which is a combination of the power follower strategy and the equivalent fuel consumption strategy. Research indicates that the driver power dependent optimization strategy can achieve much greater improvement on fuel economy compared to the ON/OFF strategy [8]. The basic idea is similar with other proposed strategies, which means the PS provides main power by converting chemical energy of the fuel to electricity for a propulsion motor. The ES acts as an electric power equalizer to supply the rest of the required power, with either positive or negative load, through its charging or discharging processes.

A diesel generator set is a complex non-linear integrated system of mechanical, electrical and power-electronic devices. The fuel consumption of the PS and the generator efficiency are both the function of the engine speed and torque. Figure 7 shows an engine fuel consumption map [13]. In a series HEV the engine running speeds are independent of wheel speeds. In actual operation, the engine runs in a widely changing operation range to satisfy the vehicle load demands and therefore it can be operated around its most efficient points along the optimal operation curve shown as a dotted line in Figure 7.

![Figure 7 – Engine Fuel Consumption Map with Optimal Operation Curve [13 Reprint]](image-url)
Figure 8 shows the generator-traction curve (solid line), which is used to determine the generator power indexed by the traction power. However, this approach may overcharge or drain the ES device while driving, so the SOC factor must be considered for the calculation of the generator power. Hence, the generator power can be written as in Equation (1).

\[ P_{PS\_rf} = f(P_{IBC\_rf}, SOC) \]  

Where \( P_{IBC\_rf} \) is the traction power reference (Intermediate Bus Circuit power) and \( P_{PS\_rf} \) is the power reference of the power source. Additionally, in order to optimize the power split between the PS and the ES for maximum fuel economy, the energy consumption of the ES device must be considered. The electric energy discharged from or charged to the ES must be recharged back or dissipated later on. This is equivalent to certain fuel consumption (positive) or saving (negative) of the PS.

As the driving conditions in the future are unknown as well as the information of the PS or the ES which will be determined by OEMs, the ELFA system uses a simplified method for the equivalent by analyzing the ES SOC. Simply speaking, the influence of the SOC to the generator power is through the shift of the generator traction power curve. If the SOC decreases, the generator traction curve moves up. In addition to the power required for traction drive, the engine provides extra power to charge the ES and move the SOC back to the optimal operating range. The dotted line in Figure 8 shows the curve is shifted up due to the low SOC. On the contrary, the curve moves down to prevent the ES from being overcharged when the SOC increases, reducing the power generated. The movement adjusts the generator power and thus stabilizes the SOC value of the energy source by regulating the relation between engine and traction power.

As the PS operation is independent of the vehicle speed, the engine can generate preferred power over many different operating points. After the PS power has been calculated through the energy management algorithm, the control system determines an optimal speed of the engine through a look-up table, which uses the power as input and creates a speed command as an output. However, the PS transient operation can be an important contributor to the vehicle fuel economy and emissions. For this reason, the speed and load of the PS should be changed as little as possible in order to run the PS more efficiently. A power hold function was developed that modifies the generator power rather than adapting the generative power continuously to the drive power request.

The ELFA hybrid system can also run with PS completely off. The engine can be directly turned on or stopped by the generator. This allows the engine to be shut off during coasting, braking, and at all vehicle stops. When more power needed, the engine can be started in a very short time by the attached generator. Other factors are also taken into consideration including SOC, braking power, auxiliary system loads, etc.

Vehicle drivetrain energy management is only one part of the ELFA hybrid control system. It plays a critical role to achieve the desired improvements in fuel economy and emissions. The DICO also included other functions such as drive function, motor brake function, auxiliary control, safety functions, etc. The details are shown in Figure A in the Appendix. The ELFA control strategy is derived from a large number of predetermined rules and guidelines. The advantage is that exact vehicle, PS, and ES characteristics are not required for the controller. This results in a robust, easily adaptable solution for a wide variety of vehicle platforms. Many functions (e.g. start-stop feature, generator traction curve, the SOC operation window, etc.) in the ELFA system can be calibrated to support all optimization criterion.
ELFA SYSTEM IN A HYBRID ELECTRIC BUS

The modular design of the ELFA system has been implemented in more than 20 different hybrid configurations with a variety of PS and ES combinations. A typical ELFA hybrid configuration for a 12 meter city bus with an ultra-capacitor energy storage system is shown in Figure 9. The generator is attached to the combustion engine and is controlled by an inverter. The three phase AC voltage produced by the generator is converted to DC link voltage of approximate 650 V. This voltage feeds the other two inverters for the traction drive motors. The DC link is also connected to the ultra-capacitor system through an inductor. During acceleration the ultra capacitor provides power to the DC link. During braking, the traction motors are operated as generators feeding power back into the ultra-capacitor system. The auxiliaries of the vehicle are attached to the auxiliary motor which is connected to the DC link via its own ELFA inverter.

![Figure 9 – A 12m Hybrid City Bus Drivetrain System](image)

The fourth phase of the generator inverter is used to operate the braking resistor. The ultra-capacitor system is connected with the two fourth phases of the traction motor inverters, including two inductance circuits. All of the ELFA components are connected to each other via the CAN bus (bold dotted line). The DICO also communicates with the other vehicle controllers (e.g. engine controller) via the SAE J1939 CAN-bus (dotted line).

Calibration is a crucial stage during vehicle development. After the integration, OEMs must complete the system calibration and determine the most appropriate settings. An in-house developed software with the name of Siadis is provided for the OEMs to assist their calibration, diagnostics, and validation of the ELFA system. The tool runs in a virtual environment on a laptop or PC and communicates with the ELFA components via the proprietary CAN bus. It offers a wide variety of functions including software download, parameter changes, measurement, data analysis and management, and diagnosis of the system and its components. The generated calibration and measurement data can be processed and evaluated continuously offline. Figure B in the appendix shows the interface of the Siadis software, including trace windows, parameter optimization window, variable display window, error buffers, etc. The software is similar to other commercial calibration tools but is specific to the ELFA product line.

OPERATION AND DISCUSSION

More than 1,500 ELFA hybrid drive systems have been delivered world wide. The ELFA system is designed for 10 years or 400,000 km of revenue service. To date, over 25 million operating hours have been recorded with over 300 million kilometers of on road use.

Driving tests have been conducted to evaluate performance of vehicles equipped with the ELFA system on standardized bus routes. The test results show that, compared to the conventional vehicles, the hybrid buses have achieved significant fuel economy improvements (up to 50 percent) and emission reductions. The fuel savings claimed by various fleets ranges from 25% to 35%. It is difficult to provide information about the fuel efficiencies of the ELFA system on a stand-alone basis since it is only a part of the whole vehicle and depends greatly on how it is calibrated and tuned.

Table 2 shows the potential fuel savings from different advanced technologies used in the ELFA system. Due to the large kinetic energy of the bus, significant energy can be recuperated through regenerative braking and stored in ES device. Another important fuel efficiency augment comes from the idle reduction function. This feature not only shuts down the engine at vehicle standstill but also during driving as long as the ES can provide the required traction power. This function delivers remarkable fuel efficiency during rush-hour traffic comprised of multiple stops and low speed travel. Again, this function requires independently driven accessories. While it is possible to operate the engine along its optimal points, the energy management strategy will only contributes to moderate fuel efficiency improvements as a consequence of the constraint of engine emissions and noises, degree of passenger comfort, and the...
capabilities of other drivetrain components. For example, it has been found that the small discharge cycles in hybrids can be very effective at extending battery lifetime. In this case, the fuel efficiency is sacrificed to extend battery replacement intervals. The electrification of auxiliaries saves fuel as the auxiliary system can be operated only when needed. The OEMs can further improve the fuel efficiency by downsizing the engine, installing more efficient tires, etc. However, the actual fuel economies vary depending on the complete bus design and numerous other aspects, including but not limited to: the ES device, the selected engine types and sizes, vehicle overall costs, controls, operating philosophy of the auxiliary system, the driver behavior, bus routes, and environment.

**Table 2: ELFA System Fuel Saving Summary**

<table>
<thead>
<tr>
<th>ELFA System Technology</th>
<th>Fuel Saving (%)</th>
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<tbody>
<tr>
<td>Use of regenerative braking</td>
<td>20</td>
</tr>
<tr>
<td>Hybrid energy management control</td>
<td>6</td>
</tr>
<tr>
<td>Anti-idling and engine shutoff technology</td>
<td>10</td>
</tr>
<tr>
<td>Optimal auxiliary system</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total Savings</strong></td>
<td><strong>&gt; 40</strong></td>
</tr>
</tbody>
</table>

Besides fuel savings, hybrid buses improve air quality with reduced emissions, producing societal benefits in both public health and environment protection. In London, a hybrid double-deck bus with the ELFA drive system was tested by Transport of London (TFL), utilizing the standardized procedures [14] on a dynamometer at Millbrook Proving Ground in the UK over the Millbrook London Transport Bus (MLTB) cycle. The cycle, which is based on the Route 159 in London, was developed to allow assessment of various emission reduction technologies over a cycle representative of a real world urban bus duty cycle [15]. Emissions are determined over the cycle by use of a full-flow constant volume sampling (CVS) system and appropriate analysis equipment. Fuel consumption is derived from carbon dioxide and other carbon containing emissions by the carbon-balance method. The test is required, in essence, to be repeated a minimum of three valid tests to be presented. For hybrid vehicles, the Net Energy Change of the energy storage system over the cycle must be less than 5% of the total energy used. Tests with the change greater than 5% will be considered invalid. The conventional bus dimensions were 10.4 m long, 4.39 m high and 2.52 m wide with a 7-litre Cummins diesel engine. The hybrid version was downsized to the Ford Puma 2.4 liter turbo diesel engine and adapted a Lithium-ion battery of 600 Volts as an energy storage device to power two 85 kW induction motors. The unladen weight of the bus was about 12 Tons with the overall capacities of nearly ninety passengers. All vehicles introduced into the fleet since 2007 employed Selective Catalytic Reduction (SCR) for NOx reduction. Fuel consumption of the hybrid bus was reduced by 31%. Compared to a standard double-deck Euro IV diesel bus, the test results of 5 different emissions are shown in Figure 10. It is noticeable that emissions were considerably reduced except NOx emission (only 12% decrease). The reason is that the engine was kept close to its optimum efficiency range. In general, this means the engine operated in a high average load and speed which leads to average operating temperature and high NOx emissions. The test also showed that the hybrid bus runs much quieter with a noise reduction of 5dB(A) because of the use of the smaller engine.

**Figure 10 – Hybrid Bus Emission Reduction**

Page 10 of 12
CONCLUSION

Increasing fuel prices and environmental concerns will significantly impact public transportation in the coming years. The modular ELFA hybrid drive system provides OEMs and end users with a cost effective solution and design flexibility. This paper has presented an overview of the ELFA system, including both the hardware and software. The series hybrid model overcomes the pitfalls of parallel or power-split hybrids and can easily be adaptable to all electric or fuel cell applications as technological advances improve the feasibility of those variants. Independent test results have shown the ELFA hybrid drive system can significantly improve fuel economy, lower emissions, and reduced service intervals. Adaptable to a variety of energy storage and power sources, in a number of different hybrid configurations, the ELFA hybrid drive system is the ideal solution to the challenges facing transportation and society today.

REFERENCES


CONTACT INFORMATION

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APPENDIX

Figure A – ELFA Control System Functions

Figure B – Siadis Software Interface