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Conversion of an electric bus to a hybrid bus

Summary. This paper presents a project for converting an electric public transport bus into a hybrid bus. It begins with an overview of design solutions for electric and hybrid drives. Next, traction calculations for the electric bus are presented. Based on the traction calculations, the parameters that the new hybrid drive system will have to meet will be determined. The drive system (engine and gearbox) for the hybrid bus was selected. A design solution was proposed, along with a theoretical presentation of the control system for the new hybrid bus drive system. Finally, a summary and conclusions are provided, along with possible future directions for solutions regarding the conversion.
Keywords: electric bus, hybrid bus, traction calculations, conversion

1. INTRODUCTION

Air pollution and increasingly stringent requirements regarding harmful exhaust emissions are causing significant changes in the vehicle fleet in cities and rural areas [1, 2]. For some time now, there has been an increasing number of hybrid and electric buses powering the fleets of urban carriers [3]. The integration of hybrid and electric vehicles (EVs) in public transport presents challenges and opportunities, but it is also important to consider which type of vehicle is better in specific operating conditions [4].

The main element influencing bus design and enabling their sale are the current requirements for reducing road emissions [5]. These restrictions require manufacturers of internal combustion (ICE) buses to implement advanced exhaust aftertreatment systems, such as a diesel particulate filter (DPF), an SCR reactor, and an AdBlue system. Increasingly stringent standards [6] have forced bus designers to seek alternative drive source solutions: hybrid drives (HEV) and fully electric drives (BEV). A hybrid drive system (HEV) consists of an internal combustion engine (ICE), an electric motor, a generator, and batteries. There are several types of hybrid systems: parallel, series, and series-parallel. Their schematic structure and differences are presented below. A parallel hybrid drive in vehicles consists of two sources: an internal combustion engine and an electric motor, which are combined into a single system [7]. The internal combustion engine and the electric motor work independently with the transmission. The electric motor is designed to provide power during stop-and-go traffic, while at high speeds the vehicle is powered solely by the combustion engine. During acceleration, both the electric motor and the combustion engine operate [1]. During driving, the system monitors the operation of the engines and decides which power source is most efficient at a given moment [7,8].

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In a series hybrid drive, the drive is provided by an electric motor [1]. The combustion engine is connected to an electric generator, which converts mechanical energy into electrical energy. This energy is then fed to the electric motor, which drives the vehicle's wheels. Unlike a parallel hybrid drive, in a series hybrid drive, the combustion engine does not directly drive the vehicle's wheels, but always operates in one of two modes: either battery charging mode or electric motor assist mode [7, 9]. The schematic design of a series hybrid drive is shown in Figure 2.

A series-parallel system is a combination of two types of hybrid drive systems. The operating principle of this type is to utilize both engines to propel the vehicle, depending on the vehicle's needs. The combustion engine can directly drive the wheels or a generator, which powers the electric motor or charges the battery. The electric motor can also directly drive the wheels or draw energy from the battery [7]. During low-speed driving or braking, the electric motor is used to propel the vehicle. If the batteries are depleted or there is a need for more power, the combustion engine is activated to provide additional power or to power the generator, which charges the battery. At higher speeds, the combustion engine is typically used directly to propel the vehicle, with the electric motor acting as a backup [7, 11].

Hybrid buses have many advantages over buses powered by conventional combustion engines, such as lower emissions of harmful exhaust gases, reduced fuel consumption, increased efficiency and reduced maintenance costs [10].

A fully electric bus (BEV) differs from its combustion engine counterpart in the design of its drive and power supply system. Central synchronous motors with permanent magnets are typically used. There are also solutions with asynchronous traction motors and electric motors installed directly on the vehicle axle and integrated into the wheel hubs. Another fundamental element of a battery-powered electric bus is its energy accumulators [12]. The impact of traffic parameters on the energy consumption of electric vehicles is decisive [13, 14, 15]. Actual operating conditions are monitored during operation [16], and on-board diagnostic systems (EOBD) are used [17]. Lithium-ion batteries are used, which are characterized by lower capacity and lower energy density. They are used on routes where frequent recharging is possible, which necessitates the construction of additional infrastructure along the vehicle's route, such as induction loops or pantographs. LFP (Lithium-iron-phosphate) batteries are also used, which have a higher energy density and significantly higher capacity. They are commonly used in buses that do not allow for additional charging or expansion of the infrastructure along the route. Charging of these types of vehicles typically takes place in depots and takes several hours [12]. Battery charging is performed using one of three methods: plug-in, pantograph, or wireless. Depending on the charging method, the vehicle must be equipped with appropriate accessories and inverters (inverters) located in the traction container [18, 19].

2. TRACTION CALCULATIONS

List of important symbols:

A – frontal area,

a – vehicle acceleration,

c_x – air drag coefficient,

F_n – driving force,

F_p – air drag forces,

F_b – inertia forces,

F_w – hill resistance forces,

f_t – coefficient determining the effect of road slope,

f_0 – basic rolling resistance coefficient: $f_0 = 0.01$,

g – acceleration of gravity 9.81 m/s^2 ,

i_g – final drive ratio,

M_s – torque of the electric motor,

m – permissible gross vehicle weight,
P_k – power at the wheels,
P_s – power of the electric motor,
r_d – dynamic radius,
v – vehicle speed [km/h], the speed in range from 0-80 km/h,
w – maximum road gradient,
δ – rotating mass coefficient,
η_m – mechanical efficiency.

Due to the very intensive use of city buses – multi-shift operation with minimized downtime to improve the economic performance of transport companies – opinions are being voiced about the limited capabilities of electric buses due to their significantly shorter range, especially in winter conditions, compared to other drive solutions. Furthermore, long downtimes during battery charging, limited battery life, and significant investments in expanding the charging infrastructure argue for the phasing out of further use of electric buses. So, does converting an electric bus to a hybrid make sense? This paper will address this question.

Figure 1 shows the assumed torque characteristics of the electric motor.

To determine the resistance forces, rolling resistance and air resistance are taken into account. To determine the rolling resistance force and power as a function of speed, the following relationship was used:

$$F_t = m \cdot g \cdot f_t \ [N] \tag{1}$$

$$f_t = f_0 \cdot (1 + k_v v^2) \tag{2}$$

where:
$k_v = 5 \cdot 10^{-5}$

In order to determine the air resistance force as a function of speed, the relationship was used:

$$F_p = 0{,}047 \cdot A \cdot c_x \cdot v^2 \ [N] \tag{3}$$

where:
c_x – air resistance coefficient, the value assumed c_x = 0,8.

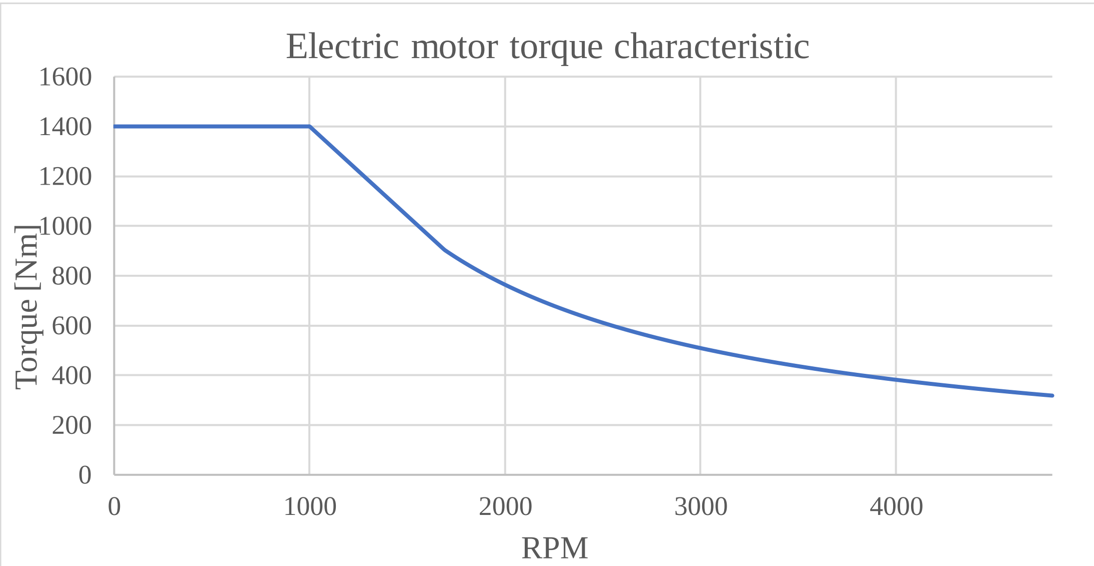

Fig. 1. Torque characteristics of an electric motor.

Total force of resistance to motion:

$$F_{op} = F_t + F_p \ [N] \tag{4}$$

The power of resistance to motion:

$$P_{op} = F_{op} \cdot \frac{v}{3600} [kW] \tag{5}$$

Balance of driving forces in an electric bus:

$$F_n = \frac{M_s \cdot i_g \cdot \eta_m}{r_d} [N] \tag{6}$$

Figure 2 shows a graph of the force balance as a function of the bus speed. To determine the power balance and obtain a graph of wheel power as a function of speed, the following relationship should be used:

$$P_k = P_s \cdot \eta_m [kW] \tag{7}$$

Figure 3 shows a graph of the power balance as a function of the bus speed.
The relationship was used to determine the dynamic characteristics:

$$D = \frac{F_n - F_p}{m \cdot g} \tag{8}$$

Relationships (9) and (10) were used to determine the acceleration characteristics. The driving forces include rolling resistance forces, motion resistance forces, inertia forces, and hill resistance forces.

$$F_n = F_t + F_p + F_b + F_w \tag{9}$$

$$F_n = mgf_t + F_p + ma\delta + mgw \tag{10}$$

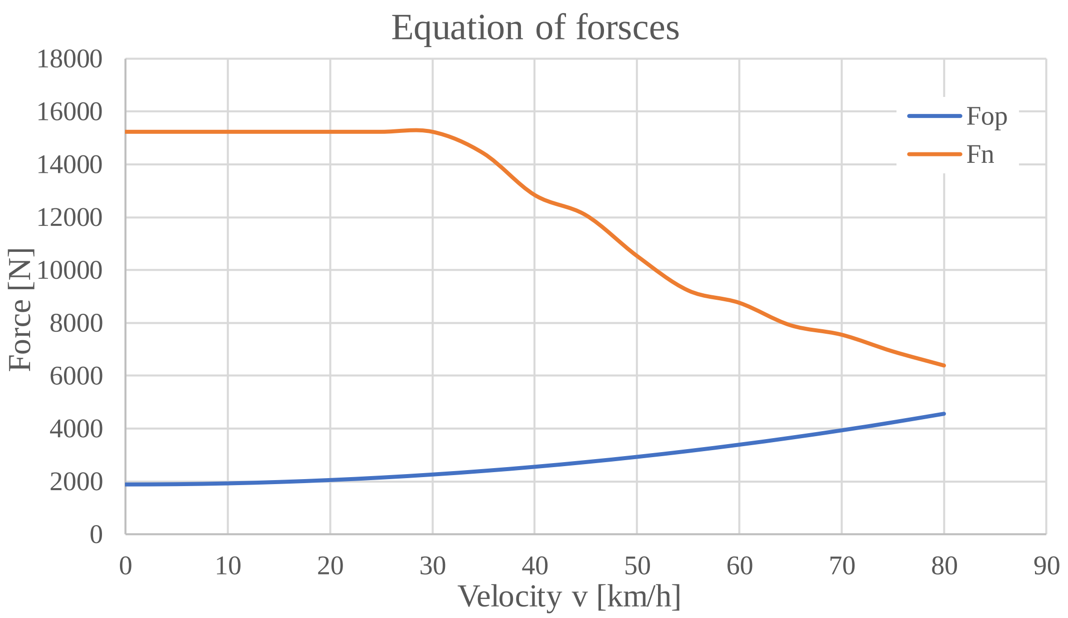

Fig. 2. Graph of the force balance as a function of the bus speed.

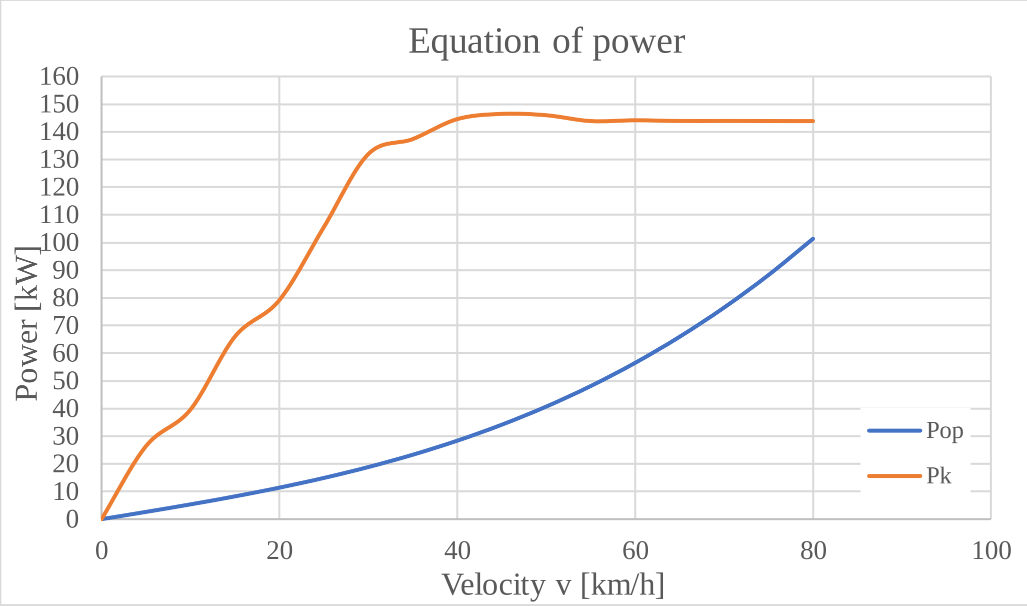

Fig. 3. Power balance graph.

3. CONVERSION PROPOSAL

The PACCAR MX-11 220 drive unit (engine) [20] was used for the conversion. Technical data are given in Table 1, and the power and torque characteristics are shown in Figure 4.

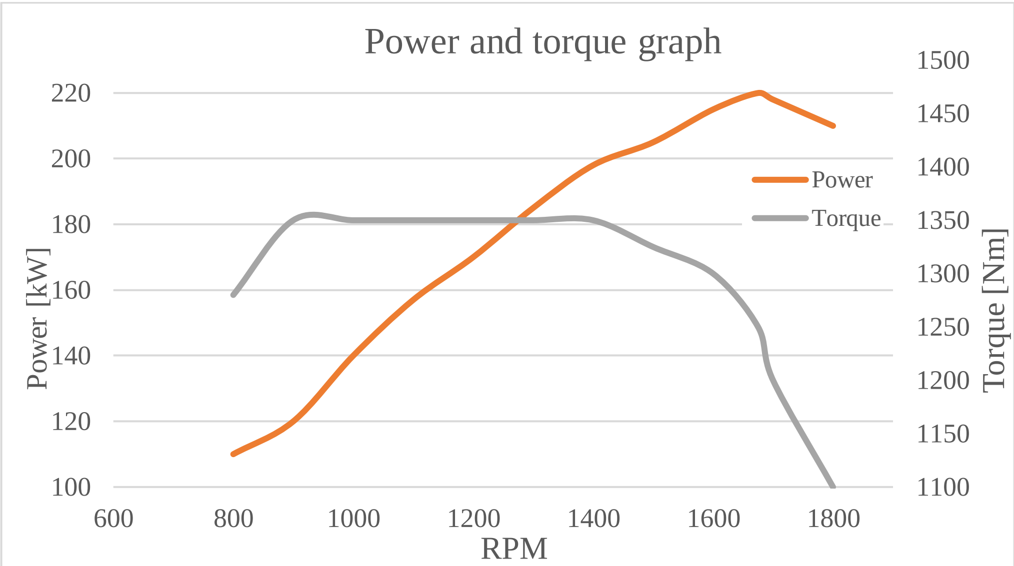

Fig. 4. Power and torque diagram of the PACCAR MX-11 220 engine [20].

To fully implement a hybrid drive, a drive unit is needed that is similar in design to a standard automatic transmission factory-installed in buses with conventional drivetrains. However, it must also incorporate electric motors to enable electric driving. An example of such a unit is the Allison H 50 EP [21].In addition to power transmission, this unit must be able to distinguish between different driving modes and control and communicate with other systems in the bus in real time.

Case 1: Bus acceleration – from 0 to approximately 16 km/h. Energy from the battery powers electric motor "B." The combustion engine operates under low load and simultaneously drives electric motor "A," which is currently operating as a generator that transmits energy to electric motor "B." The unit operates in Mode 1 – Figure 5.

Table 1. Basic technical data of the PACCAR MX11 220 drive unit used for bus conversion [20].

PACCAR MX-11 220	
Rated Power	220 kW przy 1675 rpm
Maximum Torque	1350 Nm przy 900-1400 rpm
Displacement	10800 cm^3
Bore x Stroke	123 x 152 mm
Displacement	18,5:1
Weight	998 kg

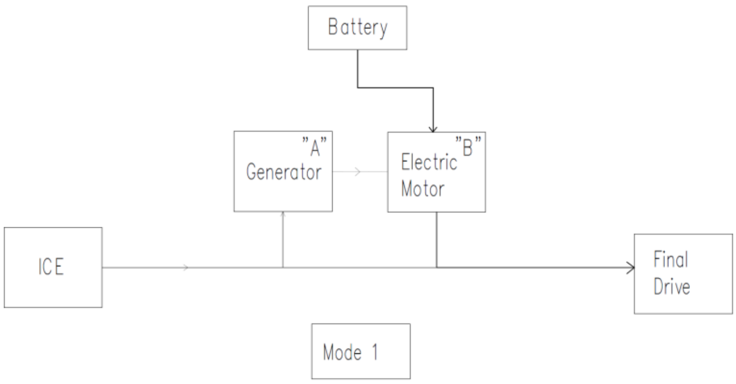

Fig. 5. Operation diagram of the Allison H 50 EP drive unit – case 1.

Case 2: At a speed of approximately 50 km/h, the driver releases the accelerator pedal. No further acceleration is required because the city speed limit has been reached. Less energy is supplied from the battery. At this stage, the combustion engine must be fuel-efficient; it drives electric motor "A," which acts as a generator and drives electric motor "B." The unit operates in Mode 1 – Figure 6.

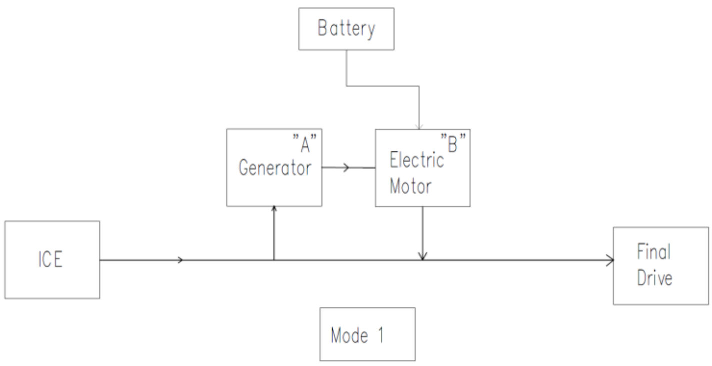

Fig. 6. Operational diagram of the Allison H 50 EP drive unit – case 2.

Case 3: Accelerating the bus from 50 km/h upwards. Electric motors "A" and "B" are simultaneously receiving power from the battery, and the combustion engine also participates in propulsion (two energy sources). The unit operates in Mode 1 – Figure 7.

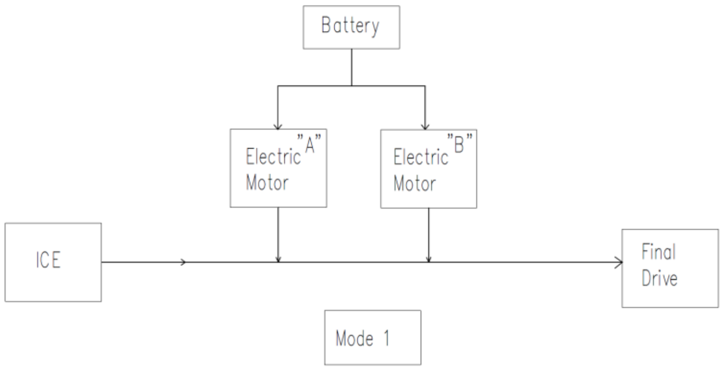

Fig. 7. Operational diagram of the Allison H 50 EP drive unit – case 3.

Case 4: Changing the driving mode from Mode 1 to Mode 2 – "compound split". Electric motor "B" is powered by the combustion engine and operates as a generator. Electric motor "A" obtains energy from the battery – Figure 8.

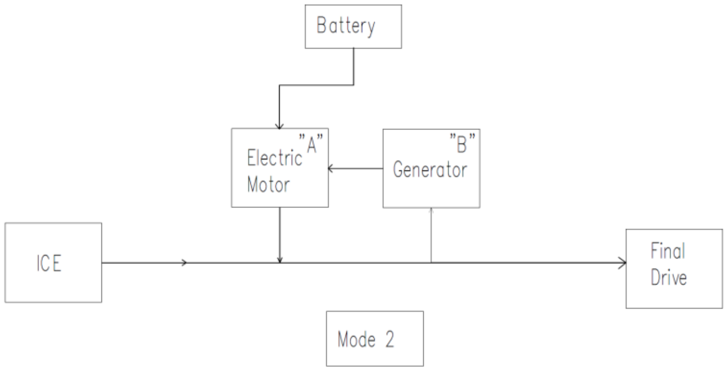

Fig. 8. Operational diagram of the Allison H 50 EP drive unit – case 4.

Case 5: Driving at a constant speed, without accelerating. The bus is driven almost entirely mechanically – the combustion engine drives the output shaft and simultaneously powers electric motor "B," which acts as a generator. The energy generated by electric motor "B" is transferred to electric motor "A," as it is mounted on the same gear ring. The unit operates in Mode 2 – Figure 9.

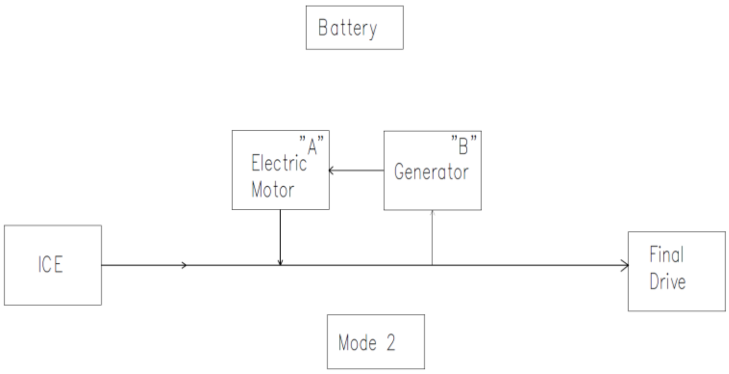

Fig. 9. Operational diagram of the Allison H 50 EP drive unit – case 5.

Case 6: Engine braking by releasing the accelerator pedal. Energy recovery occurs. Electric motor "B" acts as a generator and transfers energy to the battery, simultaneously charging it. Excess unused energy is transferred to electric motor "A," which increases the engine speed. The unit operates in Mode 2 – Figure 10.

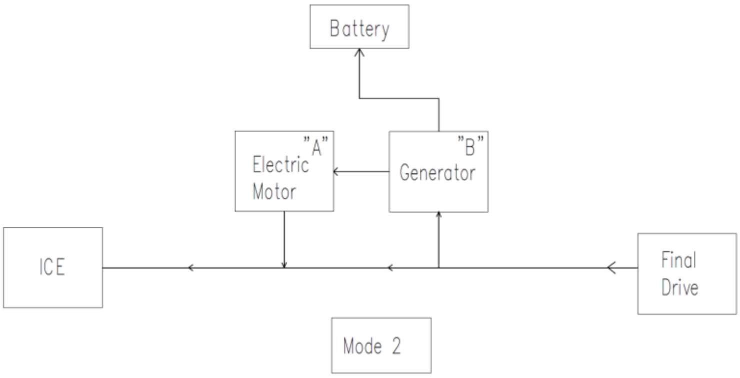

Fig. 10. Operational diagram of the Allison H 50 EP drive unit – case 6.

Case 7 (two possibilities): Braking – electric motors "A" and "B" operate as generators and supply energy to the battery. A transition from Mode 2 to Mode 1 occurs. A phenomenon can also occur during braking in which electric motor "A" operates by transferring energy from electric motor "B" operating as a generator, thus causing the combustion engine to speed up to increase engine braking efficiency – Figures 11 and 12.

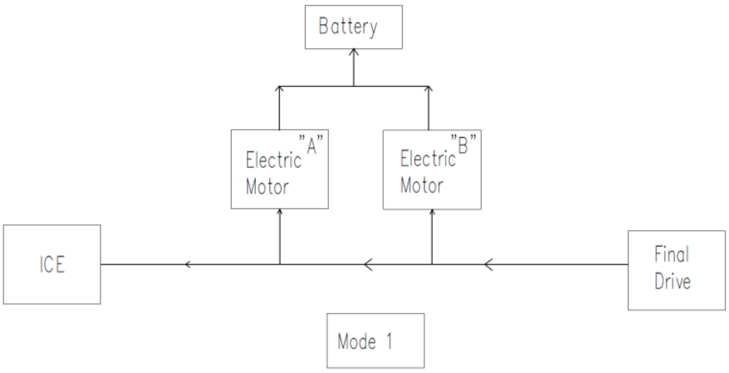

Fig. 11. Operational diagram of the Allison H 50 EP drive unit – case 7.

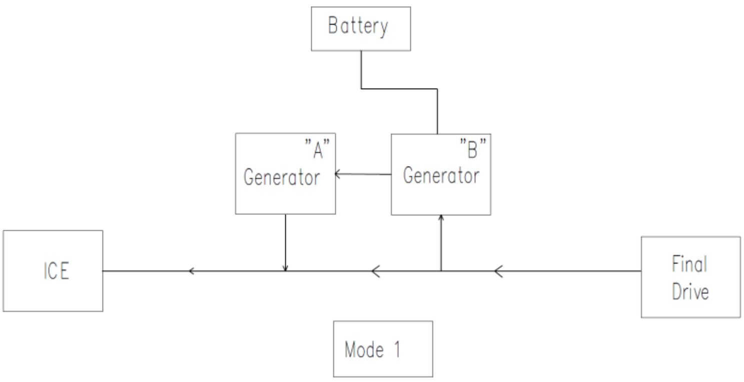

Fig. 12. Operation diagram of the Allison H 50 EP drive unit – case 7, second possibility.

Due to the bus's weight having changed by approximately 200 kg, the rolling resistance force and power were recalculated, but the air resistance force remained unchanged. The total rolling resistance force must be determined again. Figures 13 to 16 present a comparison between an electric car and a hybrid car, respectively: driving force balance – Figure 13, power balance – Figure 14, dynamic characteristics – Figure 15, acceleration characteristics – Figure 16.

The resistance forces are the same for both electric and hybrid buses (Figure 17). The driving force of an electric bus is constant at approximately 15,000 N in the speed range from 0 to approximately 31 km/h, but as speed increases, it begins to decrease gently until the assumed maximum speed of the bus – 80 km/h. In the case of the driving forces of a hybrid bus, the electric motor is responsible for moving the bus. The driving force is greatest in the speed range from 14 to approximately 20 km/h, reaching 25,000 N, as the combustion engine joins the drive. Compared to the driving force of an electric bus, the driving force of a hybrid bus is greater in the range up to 25-30 km/h, for the first-stage planetary gear ratio of the Allison drive unit.

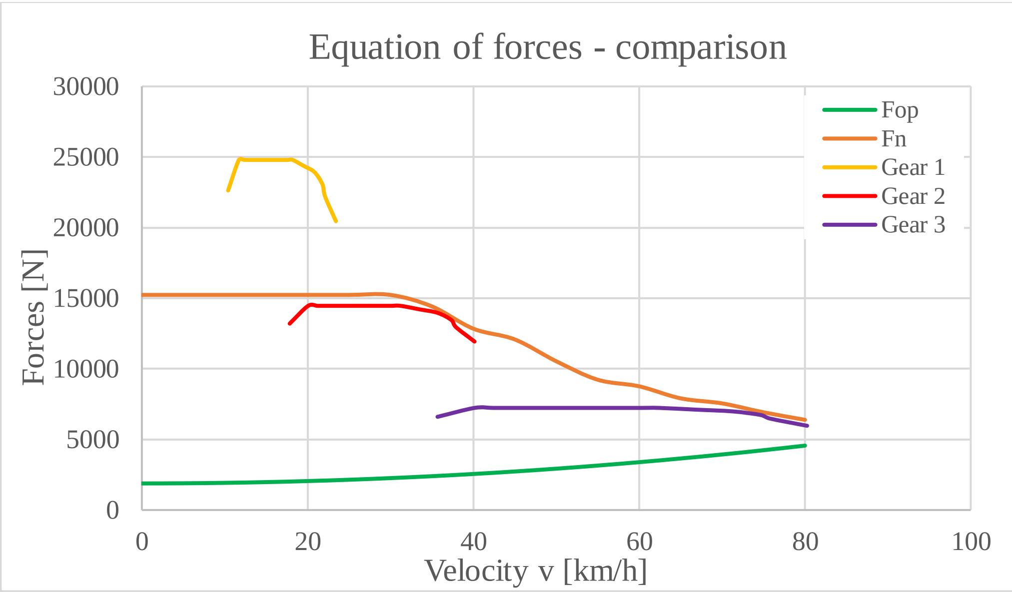

Fig. 13. Comparison of the power balance of an electric bus and a hybrid bus.

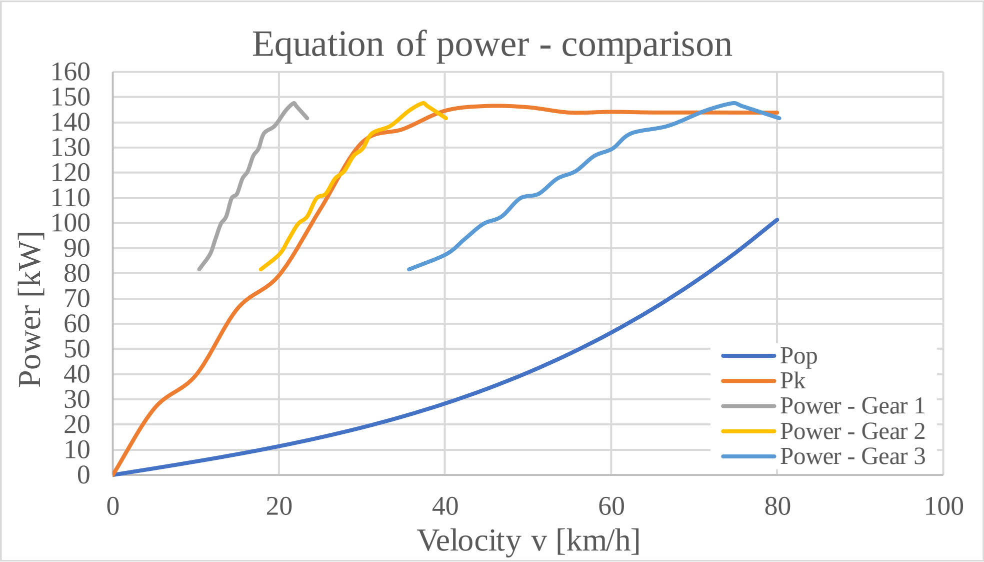

Fig. 14. Comparison of the power balance of an electric and hybrid bus.

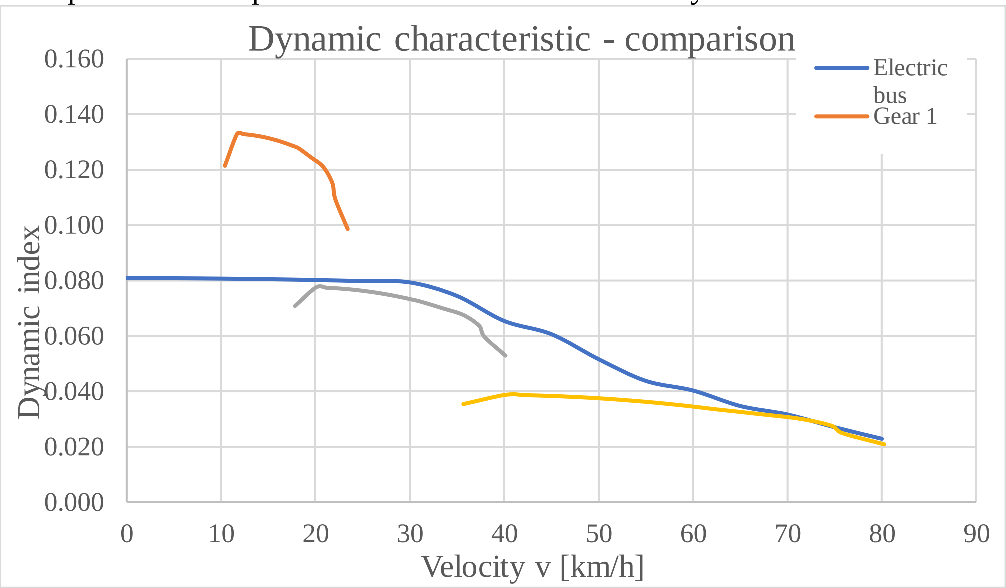

Fig. 15. Comparison of the dynamic characteristics of an electric and hybrid bus.

For the second-stage planetary gear ratio of the Allison drive unit, the driving forces are slightly lower than the driving forces of an electric bus. Around a speed of 35 km/h, the driving force values of the compared buses are similar and amount to approximately 13,000 N. For the third-series planetary gear ratio of the Allison transmission, the difference in driving force values, in the speed range from 35 to approximately 60 km/h, is significant in favour of the electric drive. Observing the force balance graph (Figure 17), the driving force for the third-series planetary gear ratio is linear, while the driving force of the electric bus continues to decrease gently. In the speed range from 75 to 80 km/h, the driving forces of the compared buses assume similar values.

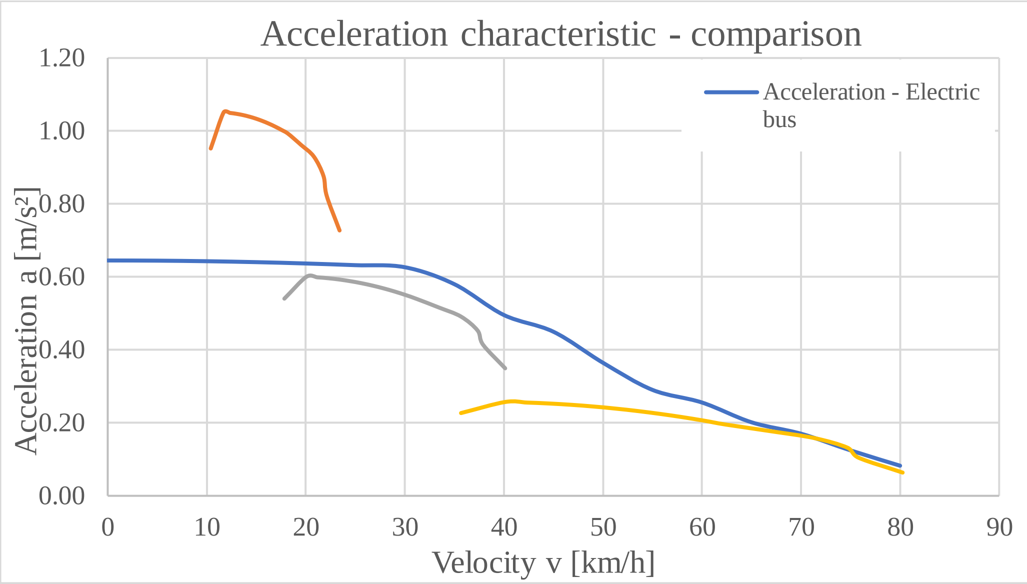

Fig. 16. Comparison of the acceleration characteristics of an electric and hybrid bus.

A comparison of the power balance (Figure 14) shows that the resistance power is the same for both the electric and hybrid buses. The wheel power of the electric bus as a function of the bus speed is marked in orange. Up to a speed of approximately 30 km/h, the power curve of the electric bus increases linearly. From a speed of 30 km/h, the power value stabilizes and reaches a value of approximately 145 kW. In the case of the hybrid bus, the wheel power is divided according to the gear ratios of the Allison H 50 EP gearbox. For the first planetary gear ratio, the bus achieves a maximum power of approximately 145 kW at a speed of approximately 25 km/h, but then begins to drop rapidly and switches to the second planetary gear. In the range of 25 to 33 km/h, the wheel power curve with the second planetary gear engaged in the hybrid bus overlaps with the power curve of the electric bus. At around 38 km/h, the hybrid bus with the second planetary gear engaged reaches a maximum power of 145 kW. From a speed of approximately 40 km/h, the third planetary gear is engaged. The power curve is less dynamic than with the previous planetary gear ratios, but it ensures a stable increase in power in the speed range of 40 to 75 km/h. This smoother curve is due to the dynamically increasing motion resistance, which is higher at higher speeds. At around 75 km/h, the bus reaches a maximum power of approximately 145 kW. The hybrid drive system and the electric bus drive reach their limits in the speed range of 70-80 km/h.

A comparison of the dynamic characteristics (Figure 15) shows that the dynamic characteristic (dynamic index) of the electric bus is constant up to a speed of approximately 30 km/h. The characteristic curve is linear and begins to decrease gently only after reaching a speed of 35 km/h. This characteristic curve may mean that the electric bus will not accelerate well after exceeding 30 km/h. The maximum dynamic index value for the electric drive is approximately 0.08. A bus with a hybrid drive achieves higher dynamic index values in the speed range up to 25 km/h. This is due to the engagement of the first planetary gearset. The dynamic index reaches its maximum value at a speed of approximately 15 km/h, reaching a value of 0.132. When the second planetary gearset is engaged, the dynamic index value drops. The dynamic characteristic curve is similar to that of an electric bus. From a speed of approximately 20 km/h, the dynamic index values decrease. At a speed of approximately 35 km/h, the third planetary gear engages. In the speed range of 35 to 65 km/h, there is a significant difference in the dynamic index values between the electric and hybrid buses. For speeds in the 70-75 km/h range, the dynamic index values are similar for both the electric and hybrid drives.

The decreases in the dynamic index values, occurring in both the electric and hybrid drives, may result from increasing resistance forces, which depend on the driving speed - Figures 13 and 14.

A comparison of the acceleration characteristics of the electric and hybrid buses (Figure 16) shows that the electric bus accelerates linearly from 0 to approximately 30 km/h at a speed of approximately 0.65 m/s². From a speed of approximately 30 km/h, the acceleration value decreases gently to approximately 0.1 m/s² at a maximum speed of 80 km/h. The hybrid bus achieves higher acceleration values in the speed range up to 25 km/h. The maximum acceleration is approximately 1.05 m/s². Maximum acceleration is only possible when the first planetary gear of the Allison drive unit is engaged. After reaching maximum acceleration, the acceleration values decrease rapidly. At a speed of approximately 20 km/h, the second planetary gear engages. Within its operating range, the hybrid bus achieves lower acceleration values than the electric bus. The acceleration characteristics in this speed range are similar to those of the electric bus. At a speed of approximately 35 km/h, the third planetary gear engages.

In the range of approximately 35 km/h to 65 km/h, the hybrid bus achieves lower acceleration values than the electric bus. At speeds of 70-75 km/h, the acceleration values are similar for both the electric and hybrid buses. The decreasing acceleration values with increasing speed may be due to increasing drag forces, which increase with speed. In the case of a bus, drag forces will be significantly greater than in a passenger car due to the bus's large frontal area and the vehicle's heavy weight.

4. CONCLUSIONS

The article proposes the concept of conversion of converting the drive system of an electric bus to a hybrid drive. Converting an electric bus to a hybrid is possible, but it clearly has its advantages and disadvantages.

The authors presented a proposal for converting a bus from an electric drive to a hybrid drive. Generally speaking, there are numerous proposals for converting a combustion engine to an electric or hybrid drive, but there are no specific concepts for transitioning from electric to hybrid. In addition to power transmission, the drive unit must distinguish between different driving modes and continuously control and communicate with other bus systems in real time. The authors proposed control algorithm schemes for seven cases of the Allison H 50 EP drive unit. These issues constitute a significant substantive contribution of the authors. To propose an approach to this issue and suggest further steps in the procedure.

Comparing drive system parameters, such as power output, a hybrid bus performs better than a fully electric bus. The estimated weight of the converted bus will also be lower than that of an electric bus, which is consistent with current automotive trends of reducing vehicle curb weight. Comparing traction calculations, a hybrid bus is only able to achieve better performance parameters at low speeds. This may be due to the planetary gear ratios of the Allison drive unit used in the calculations. Assuming different gear ratios, different characteristics and different results may be obtained.

When deciding on such a conversion, it's important to keep in mind that the risk of potential failures increases. Both the combustion engine and its associated accessories, sensors, actuators, and so on, can fail. Diagnosing complex systems and the associated repair costs can be very high. Furthermore, the hybrid system, in addition to the Allison drive unit, which consists of mechanical components such as planetary gears, also includes electric motors, sensors, and control elements, failures of which can result in the bus being immobilized and generating costs. A hybrid system is not only a drive unit, but also an inverter, battery system, wiring, and other additional components. In summary, the risk of failure in a hybrid bus is significantly higher than in an electric bus or even a bus with a conventional power source. Any failure can result in the bus being immobilized for a long period of time, which will be spent on diagnostics, which can ultimately generate losses for the carrier.

There are several potential advantages to this solution. The first advantage could be the possibility of extending the bus's lifespan, thus eliminating the need to produce a new electric bus, which emits large amounts of harmful substances into the atmosphere. Furthermore, the fact that a hybrid bus has fewer batteries means that their consumption will be significantly lower than in a fully electric bus. It will not be necessary to produce as many batteries, which are manufactured using rare earth elements. Another advantage of converting an electric bus to a combustion engine is that, assuming trouble-free operation, a hybrid bus has a significantly longer driving range than an electric bus. This would allow for more daily trips or enable the redirection of hybrid buses to suburban lines. Time would not be wasted on lengthy charging of electric buses, which would result in downtime for the city carrier.

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