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A CONTROL ALGORITHM TO FOLLOW THE LIMITATIONS OF AN ELECTRIC VEHICLE MOTOR USING THE TM4 SUMO DRIVE AS AN EXAMPLE

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Abstract – The article discusses development work on the control system of an electric vehicle considering the limitations of the TM4 Sumo power unit. Particular attention was focused on the development of a new algorithm for controlling the final phase of braking (using a retarder) at low speeds, using proprietary regulators based on the prediction of braking force values. The developed algorithm is universal (works with various drive units) automatically adjusting the setting values. At the same time, the authors paid particular attention to the elimination of the phenomenon of oscillation of the engine torque value in the final phase of braking and the synergy of the classic braking system of a commercial vehicle with electric drive braking. The article also discusses proprietary tools and software for monitoring and collecting measurement data from electric vehicles. The control algorithm is one of the products offered on the market as a solution provided by the DIGA Civil Partnership. The presented results were collected from real objects as part of implementations carried out by the authors.

Key words – Electric Vehicles, follow-up algorithm, telemetry, regenerative braking

JEL Classification – O32, O33

INTRODUCTION

The Modern transport is moving towards the use of zero-emission vehicles due to intensified work in the green economy (enforcing stringent requirements for reducing greenhouse gas emissions). On 9 December 2020, the Sustainable and Smart Mobility Strategy was published, which defines an EU Action Plan [1] with 82 concrete initiatives (over the next 4 years). The strategy aims to achieve a more climate-neutral, digital, and resilient European transport system.

In line with the EUCO301 scenario (which includes rules to achieve the EU's energy and climate goals by 2030) and increasingly stringent CO_2 emission standards (for cars, vans, and trucks), the progressive elimination of internal combustion engines in favour of electric or hydrogen drives is apparent. Electric propulsion is a solution that belongs to the group of viable and rapid implementations (not only for new vehicles, but also for retrofitting the existing fleet) [2].

In the context of the vehicles under consideration, a mechatronic system can be defined as synergistically integrated sensors, actuators, signal conditioning, power electronics, decision and control algorithms, and computer hardware and software combined to manage complexity, uncertainty, and communication [3-9].

However, electric vehicles require advanced control methods, which are being developed by many research centres [10-14]. High dynamics and torque characterristics of drives require an appropriate approach in terms of software limitations of available drive units [15-16].

It is also important to monitor the condition of the vehicle and detect and locate failures [17]. In many cases, determining the cause of system malfunction is not possible without having measurement data recorded at the time of the event, and the data shortage eliminates the possibility of quick response and elimination of the causes of errors and failures. Real-time data acquisition, along with the option of storing measurements data in files on servers, gives the ability to access at any time and performs various types of inference and statistics supporting the process of proper operation of equipment, vehicles, or machines [17].

Thanks to the digitization of vehicles, operating data are transmitted and processed by various subsystems (on-board or external), and the basic problem of diagnosis and prediction is to acquire, systematize and effectively and accurately analyse time charts [17].

1. Test track configuration

The article presents a battery electric vehicle that is powered only by electricity, stored in a non-replaceable on-board battery charged from the grid (usually at a dedicated charging station). Figure 1 shows a block diagram of an electric vehicle (example based on the electric bus).

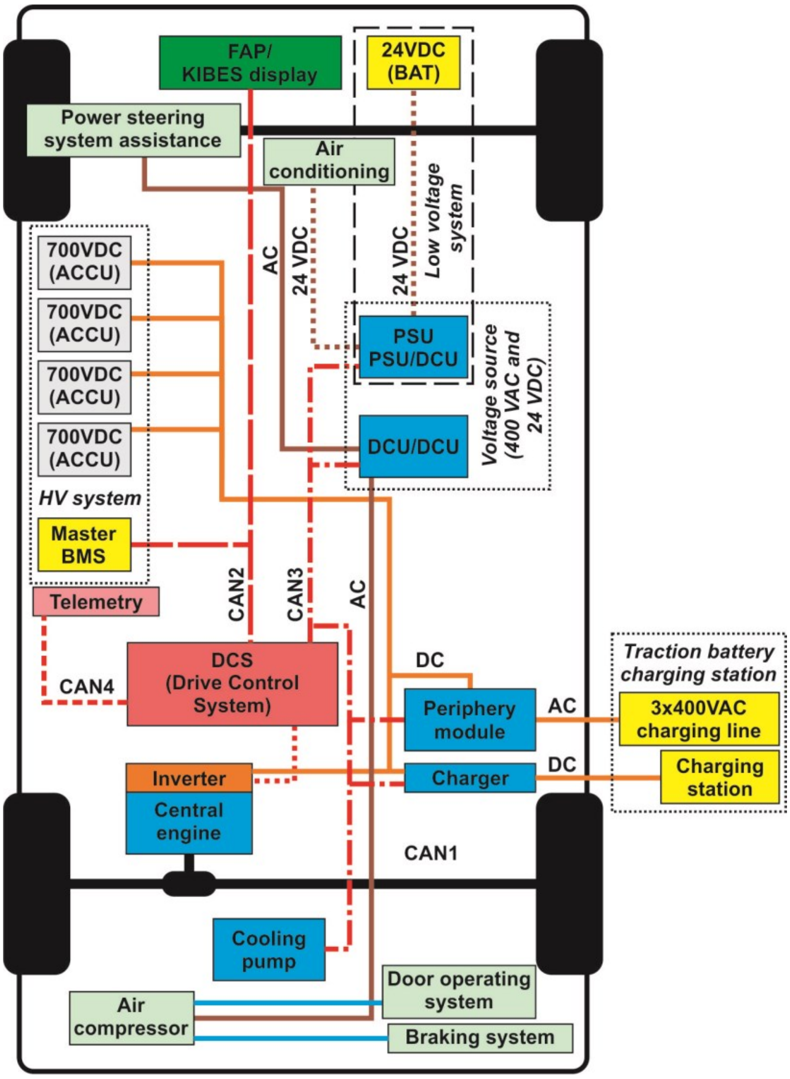

Fig. 1. Functional block diagram of an electric vehicle (**based on the public transport vehicle**), **with an indication of mechanical modifications** [own study]

The controlled element of EVs is a drive unit consisting of a drive motor and a frequency converter, requiring advanced control algorithms and monitoring of operating parameters. Overloading the drive motor in extreme cases can lead to damage to the motor inverter, the wiring and cause danger to passengers. The solution to the problem lies in tracking algorithms and systems for monitoring the operational parameters of drive systems (including telemetry) [8-9]. However, classic PID controllers (implemented by manufacturers as standard solutions for controlling vehicle drive parameters) do not offer a sufficient level of quality, which requires the development of new solutions [5-6], [18].

The scope of the study considered the TM4 Sumo motor (LSM280AHV-3400-A1, Table 1) installed in the electric vehicle.

For the diagnosis, a measurement system consisting of a PC (with installed CANLOG Analyser software and CoDeSys 3.5 SP5) and a CRUSB Spartan converter were configured. The converter can handle the full CAN bus load in terms of transmission rates up to 1000k [bit/s]. The converter is based on an 8-bit type 8051 microprocessor from Silicon Labs, which is a 48 MIPS RISC unit. The device works with Windows, Linux, Android, and Mac OS thanks to FTDI's USB module and dedicated DLL libraries (32bit and 64bit). A view of the converter used in the study, the connection diagram and the test data screen are shown in Figure 2.

All measured data are collected from the CAN4 channel of the electric vehicle. Figure 3 shows a block diagram of the measurement circuit.

Table 1. Parameters of the TM4 Sumo (LSM280AHV-3400-A1) drive motor

Parameter name	Parameter value
Motor Control Unit (MCU)	CO300HV-A1
Mechanical power	250 kW /35 seconds
Maximum torque	3400 Nm /35 seconds
Speed range	0-2450 RPM
Permissible over-speeding	2550-2600 < 2 minutes
Continuous torque	1600 Nm
Continuous power	235 kW
Efficiency	94,5%
Operating voltage	300-750 VDC
HV battery voltage	500-750 VDC
Maximum current intensity from HV battery	615 ADC at 500VDC
Continuous current intensity from HV battery	340 ADC at 500VDC
CAN interface	2.0B

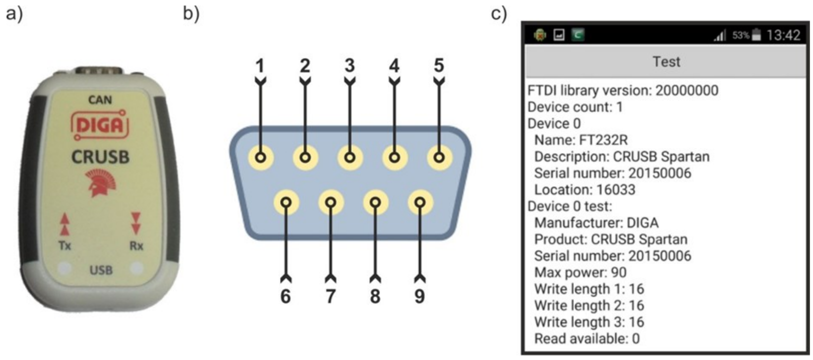

Fig. 2. View of: a) CRUSB Spartan v1.4 converter housing, b) CAN plug connection, c) converter test screen with configuration data, where: 1 - 120 Ω resistor, 2 - CAN_L, 3 - CAN_GND, 4, 5 - free pins, 6 - CAN_GND, 7 - CAN_H, 8÷9 - free pins

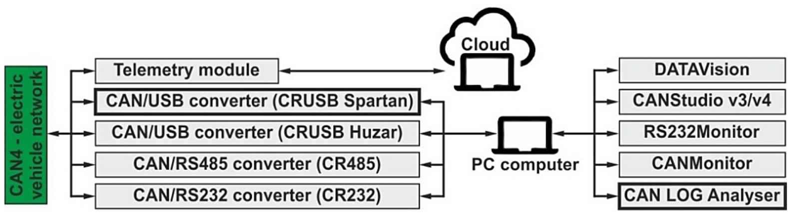

Fig. 3. Block diagram view of network configuration dedicated to monitoring and telemetry

Due to fast algorithms (in the CANLOG Analyser native application), it is possible to load up to several million CAN frames simultaneously, visualise them and quickly refresh the data on the graphs. It is also possible to check the stability of the messages sent (i.e., the time intervals between individual CAN messages). The CANLOG Analyser application is part of the proprietary CANStudio software, which includes additional functional modules in the form of applications:

- CANGraf - display of time waveforms of variables received in CAN frames,
- CANopen - network management according to the CANopen® (NMT message sending and LSS configuration of CANopen® node),
- CANData - observation of data in selected messages,
- CANConfigurator - CANopen® nodes network configuration,
- CANGenerator - addition of generators allowing selected messages to be sent to the CAN network from the CANStudio software,
- CANScript - development of custom user scripts.

2. TM4 SUMO DRIVE MOTOR PARAMETER LIMITATION ALGORITHM

Speed limits for electric vehicle drive systems are introduced for operational reasons (protection against damage to the components), homologation approval (meeting the necessary conditions for allowing the vehicle to be put into service) and safety. The last of these conditions is associated with the case of exits from viaducts, inclined areas and transport of heavy cargo and passengers. Speed limits are introduced by manufacturers or directly by vehicle integrators.

The development of the software speed limiter was aimed at obtaining a wide degree of versatility of the control algorithm, especially in the scope of handling different types of drive motors (regardless of the manufacturer). Thanks to the introduced solution, the problem of controlling the drives mounted in the wheel hubs of large buses (10-12 meters long) and buses (e.g., Mercedes Sprinter) has been eliminated. The article omitted a detailed presentation of the algorithm block implemented in the PLC, focusing the main attention on the direct effects of its operation.

The algorithms implemented in the drive control block (Fig. 4) operate based on input data in the form of available and set torque values (propulsion and recuperation), motor RPM and vehicle movement, as well as other parameters (limits and values defined in terms of drive motor limitations). Depending on the type of motor used, the algorithm adjusts its parameters and works within the designated ranges of parameter values. The algorithm calculates the appropriate numerical parameters, which are then converted into values acceptable by a given inverter.

The smooth operation of the speed limiter control system required many tests and adjustments in terms of the software of the prototype electric bus, which were made at the stage of testing on real objects (vehicles that were modernized or belong to the EV group).

The functional changes introduced to the algorithm included:

- selection of factor values for the increase in the value of drive and regenerative torque,
- reducing the planned time of the task calculating the moments (a condition resulting directly from dynamic and safety considerations),
- introduction of ramps and linearization of drive and regenerative torque.

The proposed control block implements functionality in the form of calculating the setpoint for the TM4 SUMO electric motor based on the input data of the vehicle under consideration.

The b_FREE_WHEEL variable (i.e., freewheel request) automatically puts the inverter into operation without the required torque reference. In contrast, the variable r_ACC_PEDAL_TRQ variable (present torque value based on the deflection of the accelerator pedal) stores the torque value calculated because of the accelerator pedal position, considering the limitations that may affect the reduction of the maximum torque value.

The algorithm analyses the dynamics of torque changes triggered from the accelerator pedal so as not to cause too rapid changes in the vehicle's acceleration values (eliminating passenger discomfort, mechanical damage to the drive unit [19-20], as well as other vehicle components). In the case of the vehicle's brake pedal, the value of the allowable current accepted by the BMS has been further limited (a condition required to eliminate the possibility of damage to HV batteries) in the event of excessive charging current during energy recovery.

The algorithm checks the vehicle speed on an ongoing basis (based on the values from the r_V_Speed_km_h - current vehicle speed, r_EBS_Speed_km_h_IN - vehicle speed measured from EBS, and r_Engine_Speed_km_h_IN - vehicle speed calculated on based on motor speed) and introduces corrections so as not to exceed both the maximum speed (given in the r_Max_Speed_FWD - forward speed limit or r_Max_Speed_BWD - reverse speed limit) and the value of the assumed torque.

The r_Speed_Limit_Offset_LO (lower value of the speed limit hysteresis offset) and r_Speed_Limit_Offset_HI (upper value of the speed limit hysteresis offset) variables allow the algorithm to adjust the torque value very precisely around the maximum speed point.

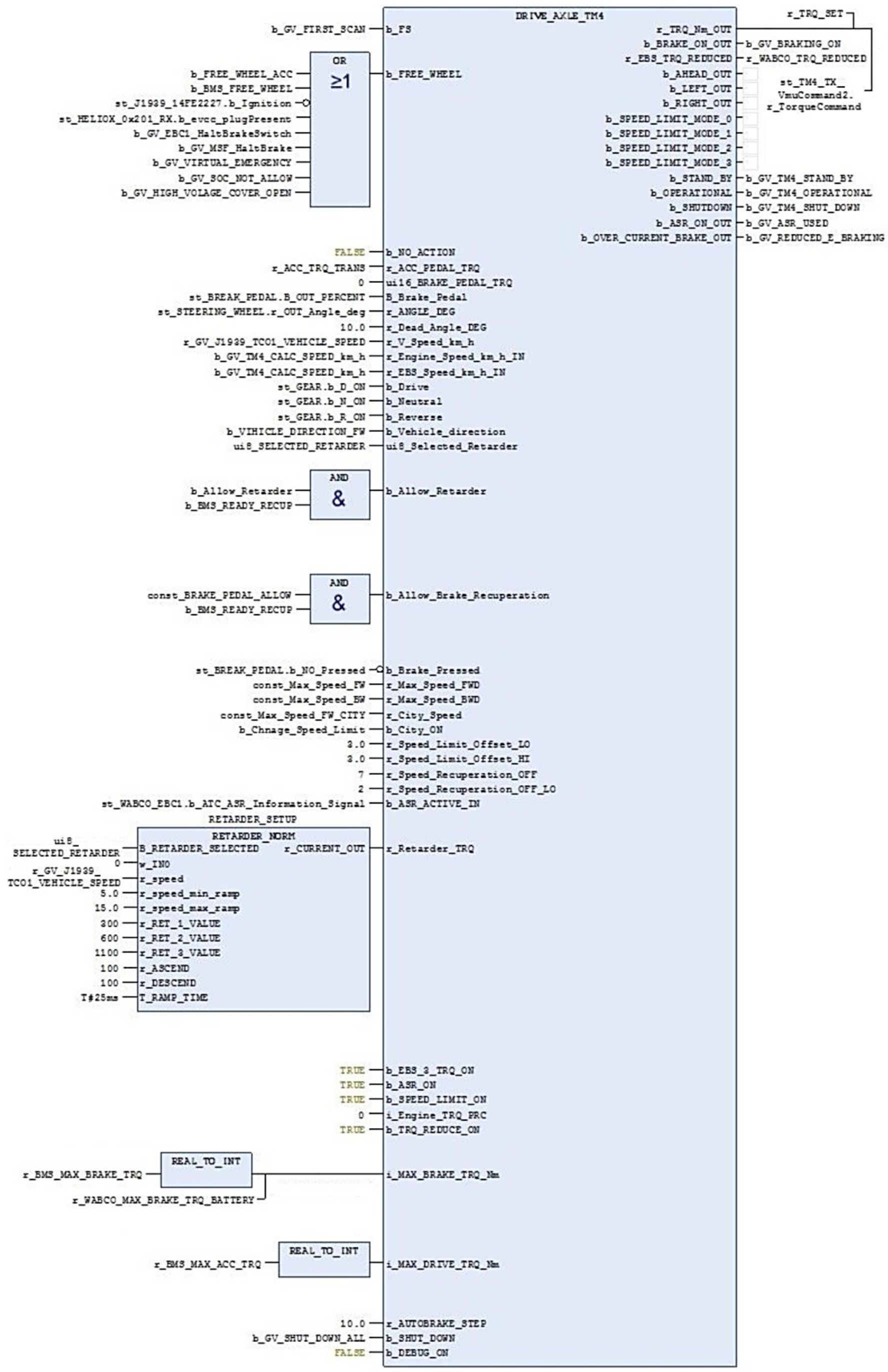

Fig. 4. View of the EV drive control block containing the electric bus speed limitation algorithm

Table 2 presents a list of inputs of the vehicle drive control block (with names, description, and type of variables).

Table 2. Description of the EV drive control block input variables

Variable name	Variable description	Variable Type
b_FS	PLC first loop of the app flag (one time initialization)	Bool
b_FREE_WHEEL	Freewheel request	Bool
b_NO_ACTION	Not used	Bool
r_ACC_PEDAL_TRQ	Torque value based on the deflection of the accelerator pedal [Nm]	Float
ui16_BRAKE_PEDAL_TRQ	Braking torque value based on brake pedal deflection [Nm]	Word
B_Brake_Pedal	Brake pedal deflection value [%]	Byte
r_ANGLE_DEG	Steering angle [°]	Float
r_Dead_Angle_DEG	Death steering angle [°]	Float
r_V_Speed_km_h	Vehicle speed [km/h]	Float
r_Engine_Speed_km_h_IN	Vehicle speed based on motor speed [km/h]	Float
r_EBS_Speed_km_h_IN	Vehicle speed measured from EBS [km/h]	Float
b_Drive	Gear Drive ON	Bool
b_Neutral	Gear Neutral ON	Bool
b_Reverse	Gear Rear ON	Bool
b_Vehicle_direction	Vehicle direction movement	Bool
ui8_Selected_Retarder	Selected electric retarder value (retarder position number)	Byte
b_Allow_Retarder	Retarder braking permit	Bool
b_Allow_Brake_Recuperation	Authorisation to use recuperation using the brake pedal	Bool
b_Brake_Pressed	Brake pedal use indication	Bool
r_Max_Speed_FWD	Forward speed limit [km/h]	Float
r_Max_Speed_BWD	Reverse speed limit [km/h]	Float
r_City_Speed	Speed limit for driving in towns [km/h]	Float
b_City_ON	Activation of the speed limit in town areas	Bool
r_Speed_Limit_Offset_LO	Speed limit hysteresis offset (lower value) [km/h]	Float
r_Speed_Limit_Offset_HI	Speed limit hysteresis offset (upper value) [km/h]]	Float
r_Speed_Recuperation_OFF	Maximum value of recuperation cut-off speed [km/h]	Float
r_Speed_Recuperation_OFF_LO	Minimum value of recuperation cut-off speed [km/h]	Float
b_ASR_ACTIVE_IN	Confirmation of the presence of the ASR system in the vehicle	Bool
r_Retarder_TRQ	Retarder braking torque value [Nm]	Float
b_EBS_3_TRQ_ON	Request to apply braking by EBS	Bool
b_ASR_ON	ASR system activation	Bool
b_SPEED_LIMIT_ON	Activation of speed limit mode	Bool
i_Engine_TRQ_PRC	Not used	Int16
b_TRQ_REDUCE_ON	Activation of torque reduction mode	Bool
i_MAX_BRAKE_TRQ_Nm	Maximum braking torque available in the vehicle (limited by BMS) [Nm]	Int16
r_AUTOBRAKE_STEP	Auto-brake torque step value [Nm]	Float
b_SHUT_DOWN	Request to shut down the drive control system	Bool
b_DEBUG_ON	Request to enable Debug mode	Bool

Table 3 lists the output variables of the vehicle drive control block (with names, description, and type of variables).

Table 3. Description of the EV drive control block output variables

Variable name	**Variable description**	**Variable Type**
r_TRQ_Nm_OUT	Calculated value of drive torque (positive value - acceleration, negative value - braking) [Nm]	Float
b_BRAKE_ON_OUT	Electric braking indication	Bool
r_EBS_TRQ_REDUCED	EBS braking torque reduction value [%]	Float
b_AHEAD_OUT	Forward driving signal	Bool
b_LEFT_OUT	Left turn signal	Bool
b_RIGHT_OUT	Right turn signal	Bool
b_STAND_BY	Indication of waiting for the driver's reaction	Bool
b_OPERATIONAL	Drive ON request	Bool
b_SHUTDOWN	Drive OFF Request	Bool
b_ASR_ON_OUT	ASR use signalling	Bool
b_OVER_CURRENT_BRAKE_OUT	Indication of limited use of recuperation (e.g., due to lack of current absorption by BMS)	Bool

In order for the entire control process to work properly, the driver must select the appropriate gear (b_Drive - forward command or b_Reverse - activation of reverse gear) signalled as TRUE value of the corresponding variable.

The recuperation process triggered by the algorithm works closely with the EBS system in the vehicle by analysing variables with information about the EBS demand for braking force (variable b_EBS_3_TRQ_ON - request to use recuperation). The maximum torque value that can be used for recuperation is stored in the i_MAX_BRAKE_TRQ_Nm variable. This moment is the maximum value without considering the limitations of the EBS system, but it is necessary for its proper operation.

The case of requesting the use of ASR or ABS systems is indicated by the variable b_ASR_ON (high state), which practically disables the possibility of feeding any torque settings to the engine.

In addition, the algorithm allows for the independent use of the braking force (recuperation) from the EBS system. The driver does this by operating the retarder lever (the selected value is given in the ui8_Selected_ Retarder variable), which allows the use of three different values of the braking torque in this case (up to eight different values).

At the end of the retarder braking process, the algorithm uses the value of the r_AUTOBRAKE_STEP variable (auto-brake torque step value) to gently release the retarder so that there are no oscillations in the engine braking system related to the vehicle's momentum and the accumulated kinetic energy. For recuperation to be possible, the b_Allow_Retarder variable (retarder braking permit) must be set to TRUE. Otherwise, the algorithm will not shut down the retarder as planned.

Table 4 summarizes the features of the algorithms implemented by commercial vehicle powertrain manufacturers and the in-house solution described.

The proposed algorithm contains several significant changes during the energy recuperation process, which are not used by the manufacturers. In the field of vehicle traffic, freewheeling was introduced as a condition for a better yield of the number of kilometres travelled in relation to the value resulting from braking with energy recovery.

In the case of freewheeling, the motor spins due to inertia and stored kinetic energy. In the case of recuperation, part of the energy is recovered, but a significant part of the energy is precipitated as heat dissipated. Even if the efficiency of the engine is 95%, in total terms, about 5% are losses. It may not seem like much, but from a simple calculation, with the voltage U=700 [V], recuperation current IDC=300 [A] - we get the engine power at the level of 210 [kW], of which the value of losses varies at the level of 10.5 [kW].

From the design point of view, the advantage of an electric motor over a combustion engine, apart from high efficiency, is primarily a constant torque characteristic in the entire speed range of the vehicle. In the case of motors built in hubs, mechanical gears have been eliminated, which also significantly reduces losses. The recuperation algorithms of bus manufacturers did not consider this fact, contrary to the modifications introduced by the authors of the article.

Table 4. Comparison of the features of the algorithms implemented by commercial vehicle powertrain manufacturers and the described in-house solution

Feature	Standard solutions (commercial vehicle drive manufacturers)	The solution proposed by the authors
Applicability	Specific type of drive system (motor with inverter) - in most cases, control variables are locked and cannot be edited by the user or integrator; the possibility of editing the algorithm at the level of adding or removing new variables is also locked	Universal block with the possibility of tuning all possible parameters for a specific model of power unit
Braking method	The predominant method is electrical braking, in which energy is recuperated into the battery or excess energy is dissipated as heat by means of an additional braking resistor - usually without using the service brake	As with standard solutions (electric braking) - with application of the service brake at the final stage (to remove oxides and deposits from the brake discs)
Free-wheel	Typically, the free-wheeling method is not possible - during the downhill or rolling phase, the manufacturer's algorithm enforces a recuperation mode or dissipation of excess energy	The use of free-wheeling as an opportunity to increase range (by free rolling the vehicle) limited only by external resistances - with simultaneous measurement of parameters to ensure the full functional safety of the vehicle's functional subsystems and the users themselves
Supported drive topologies and configurations	Depending on the specific manufacturer - usually targeting one type of topology and drive (manufacturer's specialization in its own hardware solutions)	In-Wheel Drive, Near-Wheel Drive, Central Drive, including the ability to support common drive technology: low-floor city buses, high-floor fleet (coaches), low-floor front and high-floor rear (intercity buses)
Programming language and variable preview	Source code may be partially compiled (not available for user modification); sometimes limited view of number of variables and variable refresh time	source code in Structured Text and Function Block Diagram languages, with the simultaneous functionality of viewing the operation of the PLC algorithm and forcing variable values (online operation)
Requirements for the preparation of data buses	Manufacturer's rigidly assigned buses, which, in many cases, makes it impossible to configure variable monitoring times with integrator-determined interval values (no free selection of data refresh time values)	In the case of downloading data from a configured vehicle (by the manufacturer) - no specific hardware adaptation requirements (use of available buses with data copying to CAN4 bus); and, regarding retrofitting, the introduction of standardization and functional separation of CAN buses (buses for high-speed data exchange and a separate bus for monitoring)

The authors of the article participated in an electric bus modernization project in the Netherlands, in which the problem of automatic recuperation was considered. The solution developed as part of the development work gave the driver the opportunity to decide whether to activate the electric retarder. After the test drives, a survey was conducted among professional drivers. In their opinion, this solution was the closest to the behaviour of a vehicle with a diesel engine.

The next chapter discusses the principle of operation of the software speed limiter dedicated to the modernization of e-retrofit vehicles and electric vehicles.

3. SOFTWARE SPEED LIMITER IN AN ELECTRIC BUS POWERED BY TM4 SUMO MOTOR

Figures 5 and 6 show the graphs of characteristics measured from the control system (embedded PLC), which shows the TM4 Sumo motor torque setpoint value (to meet the condition of not exceeding the assumed value of the maximum speed).

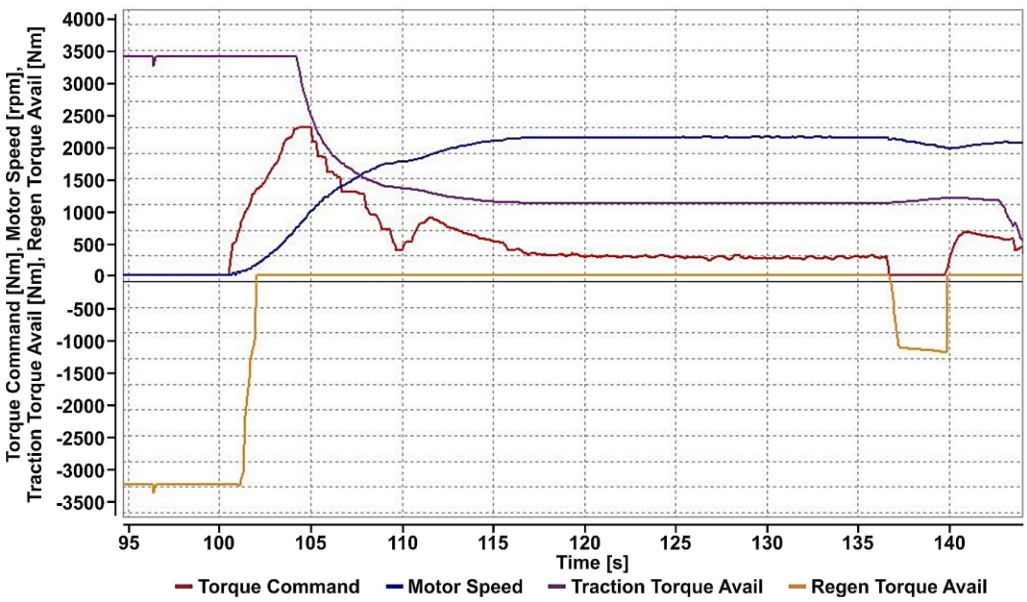

Fig. 5. Characteristics of parameters in the event of limitation of the speed of the drive motor during the acceleration process (**TM4 Sumo motor**), **where: Torque Command - torque setpoint** [**Nm**], **Motor Speed - TM4 motor speed** [**rpm**], **Traction Torque Avail - maximum value of available drive torque** [**Nm**], **Regen Torque Avail - maximum recuperation torque available in the motor** [**Nm**]

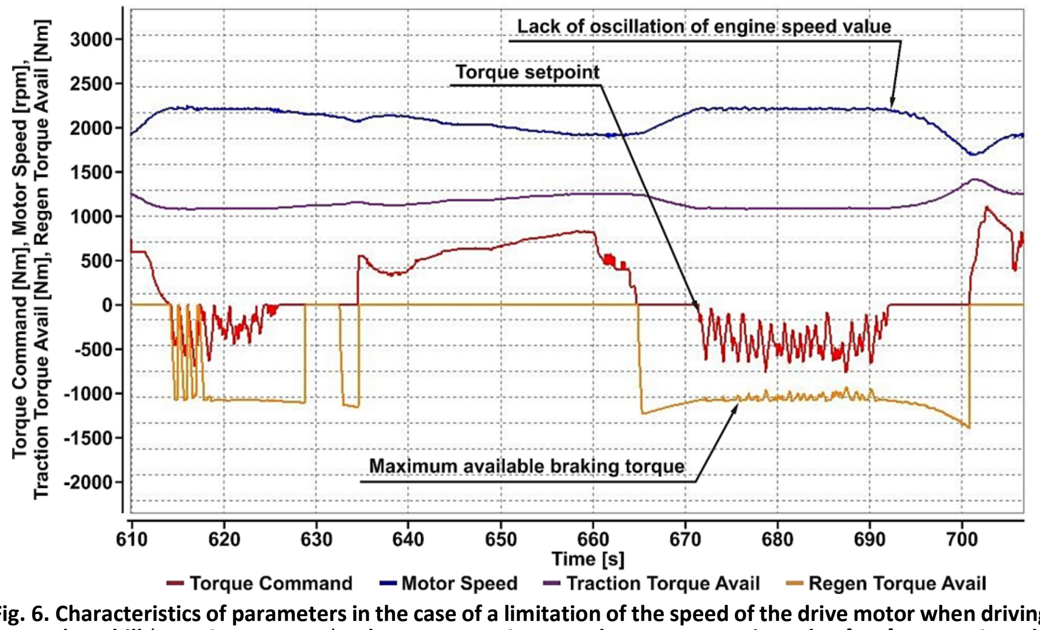

Fig. 6. Characteristics of parameters in the case of a limitation of the speed of the drive motor when driving downhill (**TM4 Sumo motor**), **where: Torque Command - torque setpoint value** [**Nm**], **Motor Speed - motor speed** [**rpm**], **Traction Torque Avail - maximum available drive torque** [**Nm**], **Regen Torque Avail - maximum recuperation torque available in the motor** [**Nm**]

PLC monitors the torque value in all possible driving cycles, including flat terrain, climbs and descents (Fig. 6). If irregularities are registered, a special motor braking mode is activated (without the possibility of controlling and disabling this mode), resulting in a rapid increase in recuperation current (occurring until the vehicle stops).

If the HV battery is fully charged, this will result in damage (i.e., burning) of the inverter. To prevent this from happening, the control algorithm must provide adequate torque reduction, activate automatic recuperation, or brake resistor.

Operation of the first version of the speed limit algorithm (without functional modifications) is shown in Figure 7. The characteristic waveforms show the oscillations of the engine speed (Motor Speed variable) directly related to the malfunction of the control system (Torque Command set point). The control system was symptomized by noticeable driving discomfort (lack of fluidity resulting from changes in the speed of the vehicle's movement).

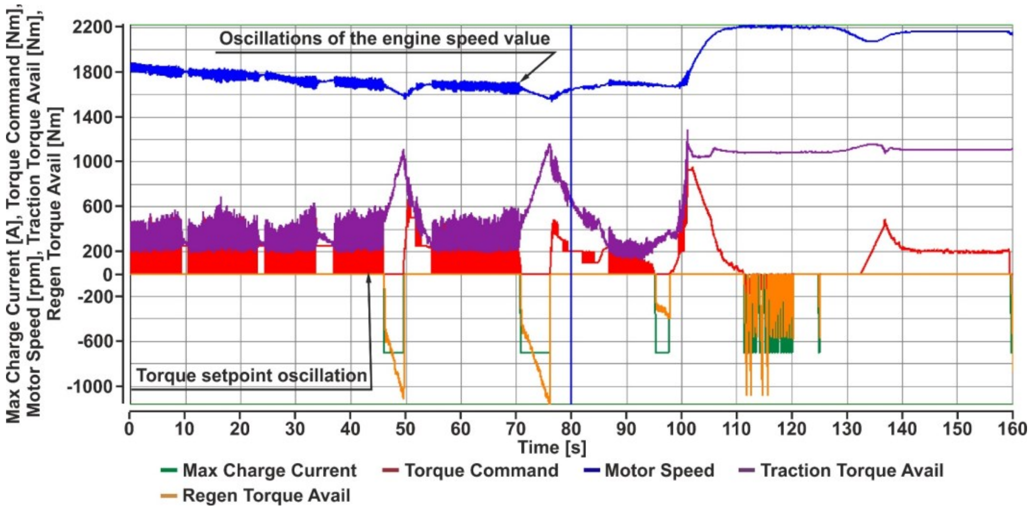

Fig. 7. Characteristics of parameters in the case of a speed limitation of the drive motor when driving downhill (TM4 Sumo motor), where: Max Charge Current - value of maximum recuperation current [A], Torque Command - torque setpoint value [Nm], Motor Speed - motor speed [rpm], Traction Torque Avail - maximum available drive torque [Nm], Regen Torque Avail - maximum recuperation torque available in the motor [Nm]

After introducing changes in the algorithm, the waveforms of characteristics Figure 5 and Figure 6, are characterized by a reduced amplitude value, which translates into a reduction in noticeable inconvenience while driving.

4. MOTOR FOLLOW-UP REGULATION OF TM4 SUMO MOTOR LIMITATIONS

The safe and efficient control of the powertrains of electric vehicles must consider the hardware limitations of the drive components. The chapter presents the progress of development work in the field of control system, which considers the limitations of the power unit with the TM4 Sumo central motor.

At the stage of the first tests, an attempt was made to adapt the algorithm developed to control independent electric motors placed in the wheels of the vehicle. The first identified anomaly (Fig. 8) is overregulation of the torque set point value (Torque Command variable) above the inverter set point (Traction Torque Avail variable), which indicates errors in the control system. The condition was unfavourable and consequently could lead to damage to the inverter circuit (despite the implementation of many different overload protections).

In the case of an electric vehicle, further use may have led to the challenge of complaint claims (included in the warranty conditions), because the system records extreme states in the inverter memory.

To eliminate irregularities, a set of programming works was carried out, consisting in tuning, and adjusting the parameters of the control system to the constraints of the inverter. For this purpose, the following were made:

– corrections in the algorithm for controlling the permissible torque value relative to the set value,
– remodelling of the algorithm for tracking the setpoint,
– software limitation of the absolute torque value

of the motor.

As a result of adjustments, the setting parameters were tuned according to the requirements and limitations of the drivetrain.

Figure 9 shows the effect of the work. The retarder is activated to brake the vehicle and its operation can be included in the sequence:

– the first level was engaged at the stage of sending the brake request,
– sequentially there was a second level activation,
– at the time of the attempt to start the third level of the retarder, the control of the value of the torque given from the inverter was activated (limitation of the setpoint).

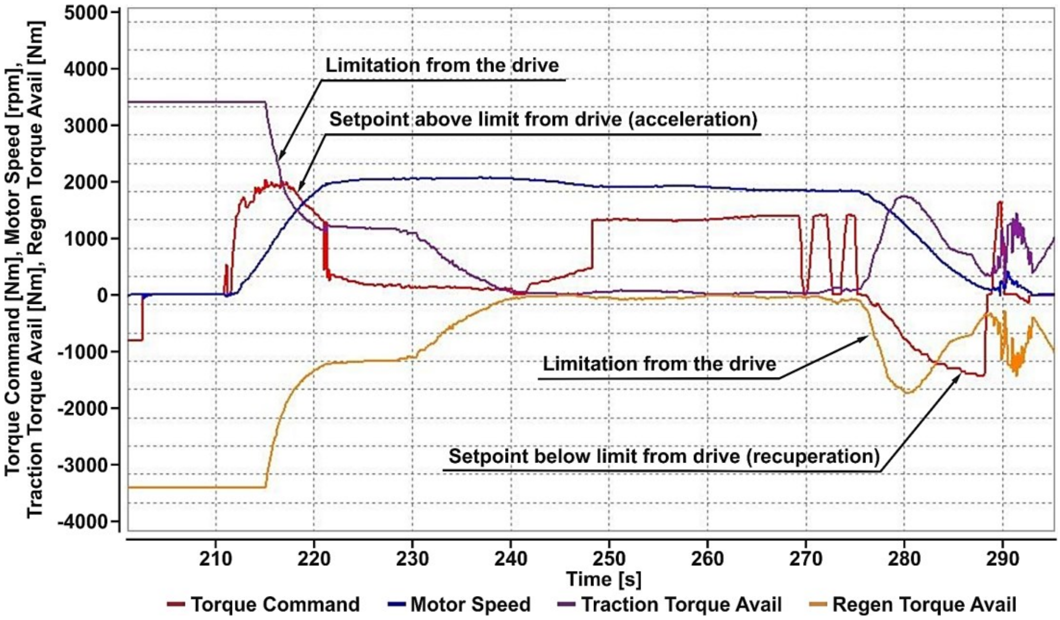

Fig. 8. Characteristics of parameters in the event of a limitation of the speed of the drive motor when driving downhill (TM4 Sumo motor), where: Torque Command - torque setpoint value [Nm], Motor Speed - TM4 Sumo motor speed [rpm], Traction Torque Avail - maximum available drive torque [Nm], Regen Torque Avail - maximum recuperation torque available in the motor [Nm]

As a result of further analysis of the waveforms of the recorded parameters (Fig. 9), one more abnormality was found, manifested by oscillations of the torque setpoint value from the control system during the reduction of vehicle speed (i.e. braking) of the vehicle to a complete stop.

Therefore, the drive system and the control algorithm were reviewed. The used control algorithm was transferred from an electric vehicle, which was driven by motors in the hubs. Each of the motors had a torque of 6 [kNm], which gave a total of 12 [kNm] of available torque.

The control system with motors in the hubs brakes the vehicle very smoothly, reducing the setpoint value to 0 [Nm] at a speed of about 10 [km/h]. When the electric braking was switched off, further speed reduction was carried out by the EBS system (in this case, the WABCO system was used). The first control algorithm developed by the author was able to brake the vehicle practically to 0 [km/h] without visible jerks of the vehicle.

In the vehicle with TM4 Sumo motor, the solution was insufficient, as it caused unacceptable torque oscillations in the final phase of braking (Fig. 9). The TM4 Sumo motor has a torque value of 3.7 [kNm], which in combination with the transmission used (with a gear ratio of 6.14) gives a torque available on wheels of 22.718 [kNm].

A new approach had therefore to be developed for the control algorithm in the final phase of braking at low speeds. Because the software controllers used are author's solutions (they are not classic PID controllers) and are based on the prediction of the demand for dynamometer force, additional factors (such as inertia and available torque value) had to be considered. The introduced corrections allowed to remove the problem of oscillation in the final braking phase (Fig. 10).

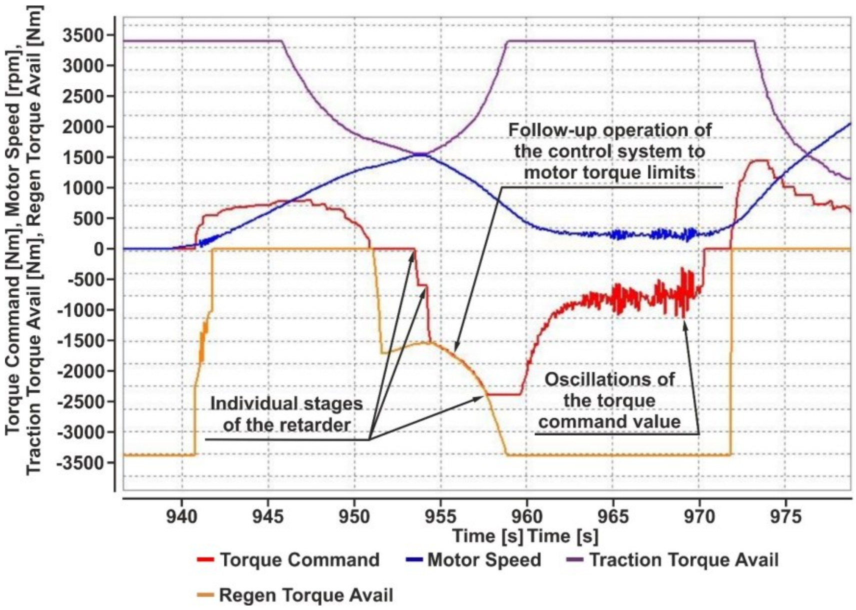

Fig. 9. Characteristics of parameters in the case of a limitation of the speed of the drive motor when driving downhill (TM4 Sumo motor), where: Torque Command - torque setpoint value [Nm], Motor Speed - TM4Sumo motor speed [rpm], Traction Torque Avail - maximum available drive torque [Nm], Regen Torque Avail - maximum recuperation torque available in the motor [Nm]

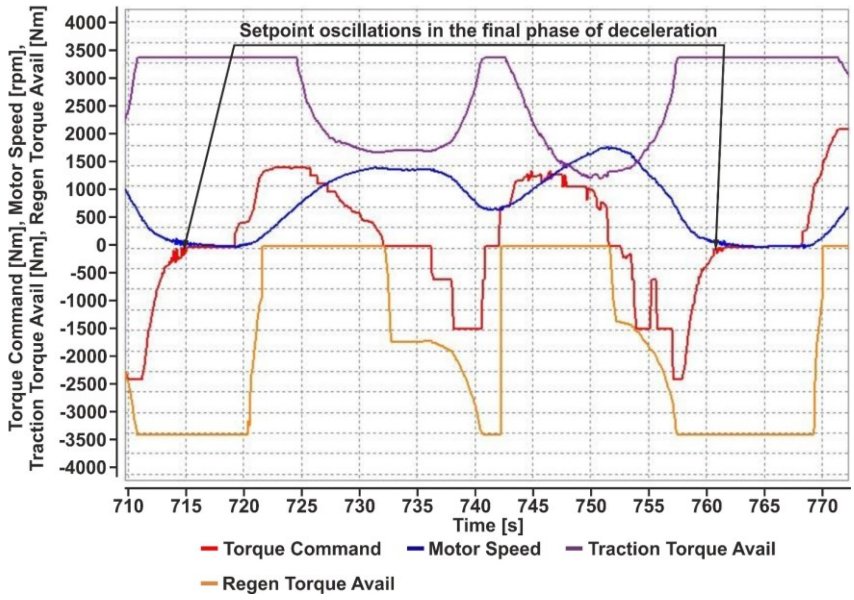

Fig. 10. Characteristics of parameters in the case of limitation of the speed of the drive motor during the final braking of the TM4 Sumo motor, where: Torque Command - torque setpoint [Nm], Motor Speed - TM4Sumo motor speed [rpm], Traction Torque Avail - maximum available drive torque [Nm], Regen Torque Avail - maximum recuperation torque available in the motor [Nm]

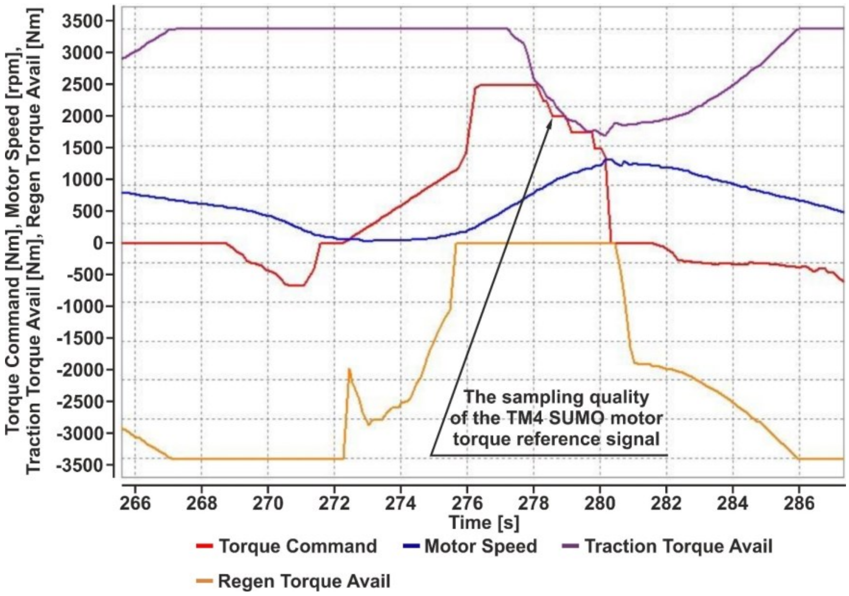

Fig. 11. Influence of signal sampling on the shape of the waveform of the TM4 Sumo motor torque setpoint, where: Torque Command - torque setpoint value [**Nm**], **Motor Speed - TM4 Sumo motor speed** [**rpm**], **Traction Torque Avail - maximum available drive torque** [**Nm**], **Regen Torque Avail - maximum recuperation torque available in the motor** [**Nm**]

The developed algorithms and regulators are characterized by high versatility, which results in the fact that they operate with various drives adjusting the parameters to a given situation in an automatic way. For this reason, there is no need to determine the settings of the regulators.

Figure 11 shows the cycle of the torque control system in the acceleration phase considering the constraint from the inverter.

The stepped waveform characteristics (Fig. 11) result from the low resolution of sampling the signal recorded in the log (about 250ms/sample). In fact, the control system operates with an interval of 15÷20ms/sample.

CONCLUSIONS

An important aspect (in the recuperation phase) of the electric vehicle control system is the issue of limiting the speed of the drive motor. When the TM4 Sumo motor is used, exceeding the critical motor speed triggers the automatic electric braking system.

A significant disadvantage of this solution is the lack of control over the factory motor braking system. If the current cannot be directed to the traction batteries or the brake resistor, irreparable damage to the motor inverter may occur, because of overheating and consequently even to a fire.

For this reason, the control system:

- must constantly monitor and control the parameters affecting the current engine speed (for this purpose, continuous monitoring and control were introduced),
- use a speed limit algorithm both when accelerating the vehicle on demand (forced by the accelerator pedal) and when driving downhill,
- must adequately balance the torque during the acceleration and electric braking phases.

In this case, the operation of the limiter system also translates into energy recovery. Thanks to the introduced improvements, the period of replacement of brake elements, which are quite an expensive operating element of the vehicle, is extended. However, it turned out that in the longer period of use of the vehicle (when the service brake linings are not used) this consequently leads to corrosion of those elements, which can affect safety - a problem with applying the service brake.

The results of the analyses allowed, among others, to determine the estimated energy savings (recuperation) in the studied group of vehicles. The obtained data shows that value of recovered energy is in the range of 18-25% of the energy used to drive an electric vehicle (energy recovery at the indicated level, with a vehicle range of 250 kilometres, gives an additional 45-62.5 kilometres of range).

Therefore, an important activity of work on vehicles is the selection of appropriate operating parameters of the drive system, modification and tuning of algorithms and introduction of proprietary solutions for monitoring operating parameters. The amount of recovered energy also depends on the weather conditions in which the vehicle goes.

The implemented algorithms indicated several significant and required changes during the energy recuperation process. The task of the recuperation system is not to recover energy every time the accelerator pedal is released, and recuperation should be used consciously to precipitate the speed of the vehicle. This is due to the following conditions:

– use so-called freewheeling,
– design of many drive systems is conducive to the conditions of freewheeling of the vehicle (i.e., the distance travelled on freewheel gives a higher yield than the amount of recuperated energy because of braking).

A particularly important observation was that at low-speed values (30 [km/h] zone in Germany), the automatic activation of the recuperation caused the accelerator pedal to constantly touch for acceleration, because the deceleration was quite fast. In the case of using freewheel (the author's solution), the deceleration time at low speeds was minimal (air resistance and wheel construction).

Therefore, it can be concluded that the preparation, change and optimization of vehicle control and monitoring algorithms have a direct impact on their operational status. Analysis of characteristics from real tests on vehicles based on CAN logs gives a large field for diagnostics of the current operating status, optimization of operating parameters and prediction.

Vehicles are currently equipped with IoT devices for data acquisition and transfer to a server (e.g., VIRICITI, SETIVO). Data from the CAN network is sent to the cloud, after which it is possible to download ROW data (i.e., all previously recorded and unprocessed CAN frames).

Thanks to the cooperation of DIGA and SETIVO, it was possible to prepare a dedicated algorithm in the CANLOG Analyzer software to decode binary data so that it could be displayed in the software.

ALGORYTM STEROWANIA NADĄŻNEGO ZA OGRANICZENIAMI SILNIKA POJAZDU ELEKTRYCZNEGO NA PRZYKŁADZIE NAPĘDU TM4 SUMO

W artykule omówiono prace rozwojowe nad układem sterowania pojazdu elektrycznego z uwzględnieniem ograniczeń jednostki napędowej TM4 Sumo. Szczególną uwagę poświęcono opracowaniu nowego algorytmu sterowania końcową fazą hamowania (za pomocą retardera) przy niskich wartościach prędkości, poprzez zastosowanie autorskich regulatorów opartych na predykcji wartości siły hamowania. Opracowany przez Autorów algorytm jest uniwersalny (działa z różnymi jednostkami napędowymi) automatycznie dostosowując wartości nastaw. Jednocześnie autorzy zwrócili szczególną uwagę na eliminację zjawiska oscylacji wartości momentu obrotowego silnika w końcowej fazie hamowania oraz synergię klasycznego układu hamulcowego pojazdu użytkowego z hamowaniem napędem elektrycznym. W artykule omówiono również autorskie narzędzia i oprogramowanie do monitorowania i zbierania danych pomiarowych z pojazdów elektrycznych. Algorytm sterowania jest jednym z produktów oferowanych na rynku jako rozwiązanie dostarczane przez DIGA Spółka Cywilna. Prezentowane wyniki zostały zebrane z obiektów rzeczywistych w ramach przeprowadzonych przez autorów wdrożeń.

Słowa kluczowe: pojazdy elektryczne, algorytm follow-up, telemetria, hamowanie rekuperacyjne.

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