SIMULATION OF TROLLEYBUS TRACTION INDUCTION DRIVE
WITH SUPERCAPACITOR ENERGY STORAGE SYSTEM.

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The article considers the possibilities of saving the regenerative braking energy in Škoda 24Tr type trolleybuses by installing the onboard supercapacitor energy storage system (ESS) and improving its performance with automated switching to the autonomous traction mode. Proposed is an ESS control system with constant DC bus voltage in the supercapacitor charging mode and supercapacitor current proportional to the AC drive current in the discharging mode. The authors investigate stability of the trolleybus ESS control system operating together with AC traction drive in various overhead voltage failure modes. The co-simulation of ESS operation was done by Matlab/Simulink AC drive and PSIM ESS continuous models.

1. INTRODUCTION

The most cost efficient kind of public electric transport is a trackless vehicle - trolleybus. The infrastructure introduction costs of trolleybus line are approaching only one tenth of those for tram systems and are only a fifth greater than for conventional diesel buses. Significant technological and economic advantages of trolleybus network installation instead of rail track building are especially obvious in narrow streets of Europe old city centres (e.g. in Riga Centre). For renewing the Riga trolleybus fleet, 150 brand-new “Škoda 24Tr” 12 m long trolleybuses were ordered and appeared in the Riga city from 2007 to 2009. However, only 90 new trolleybuses were delivered with an auxiliary diesel generator unit. Other 60 buses had only a diesel-generator, with empty place for a diesel unit or accumulator battery, etc., to be installed for extra cost.

The new trolleybuses with an induction traction drive system possess regenerative braking capability, thus providing up to 40% reduction in the energy consumption. However, the regenerative braking energy cannot be completely used in typical existing traction drive systems because none of the substations is equipped with a reversible rectifier. The real energy saving strongly depends on other trolleybuses connected to the same section of overhead line. If a number of trolleybuses are connected to the DC overhead line, a portion of the regenerative braking energy could be transferred to other trolleybuses when they are operated in the traction mode, but in the case when several trolleybuses are simultaneously braking, this energy cannot be utilized and is wasted in a brake rheostat. It is often impossible for the trolleybuses to instantly consume regenerative energy at low

traffic density in the off-peak hours and on easily loaded lines, since in the overhead supplying zone of a single traction substation at one trolleybus braking other trolleybus not often can simultaneously utilize the energy in the traction mode [1] or even are not located in this overhead line section.

Using the methodology described in [2] the wasted energy for 18 of 34 substations feeding tram and trolleybus overhead lines has been estimated [3]. The total wasted energy in Riga tram and trolleybus network fed by conventional substations is estimated to be in the order of 2GWh per year.

Three basic solutions exist for saving the untapped braking energy:

- modification of substations by replacing old rectifiers with reversible ones;
- installation of stationary energy storage systems (ESSs) at substations or near the optimal connection points of the overhead power supply line;
- fitting of the electric vehicles with on-board energy storage devices.

Equipment of substations with reversible rectifiers has several drawbacks. The main of them are:

- the necessity to modify substations, including replacement of power transformers or installation of additional ones;
- simple reversible thyristor rectifiers have a low power factor and distorted line current [4], while transistor rectifiers with a sinusoidal current waveform are rather complicated and expensive;
- none of the substation reversible rectifier types are able to “shave” the peak power; on the contrary, they increase voltage fluctuations in the power system due to the opposite flow of the regenerated energy.

To achieve useful utilization of regenerative energy and reduce the overall energy consumption, the braking energy should be temporarily saved in an ESS until another power consumer is connected to the overhead line. Such a storage system is able to cope with the common task of peak power reduction and overhead voltage stabilization. ESSs could be installed stationary at substations, weak spots of network or on-board vehicle.

As distinguished from the rail transport and the lightest rail transit systems with predictable acceleration and deceleration areas (mostly near stations, natural and technical obstacles), the city traffic with its low speeds, frequent accelerations and sudden braking is characterized by starting and braking zones distributed along the transport network. The energy transfer from a trolleybus to another vehicle or substation at a distance from several hundred metres up to a few kilometres is associated with considerable energy losses, which decrease the power saving up to 10% [5]. Therefore, the most effective way of utilising the regenerative energy without transfer losses is installation of on-board ESSs – especially for trolleybuses due to higher resistance of two-wire feeding network than that of the rail overhead.

Modern electric vehicles have good dynamical properties and increased average speed, which impose the highest current constraints on the overhead line and lead to large line voltage drops in the traction mode [6]. The starting power peaks present a problem of availability of enough power at a feeding network, otherwise the mentioned voltage drops occur that significantly impair a trolleybus dynamic performance and could cause the difficulties to maintain the operation of trolleybuses with AC drives at all. Trolleybuses with induction drives are more

demanding for network voltage quality because the lower input voltage of the frequency converter is restricted to provide normal operation of a traction drive.

If the ESS is installed at a substation it cannot eliminate undervoltage far from this substation. At the same time, an on-board ESS makes possible direct utilization of stored energy at the place of consumption, which improves the dynamic behaviour of a vehicle, with the same acceleration in a weaker network or a higher acceleration in well-fed overhead lines. Such an on-board ESS allows increasing the trolleybus traffic density without resort to building new expensive substations, which is important in the cases when traffic should periodically be intensified for a limited time.

Important advantages of on-board ESSs are the possibilities of autonomous traction and of storing the total regenerative braking energy (limited only by the storage capacity). The braking energy transfer to an on-board ESS is independent of the overhead availability, which is especially important for Riga owing to the complex overhead network design that allows simultaneous operation of trams with trolley pole and pantograph-type current collectors. The Riga overhead network has numerous crossings of tram and trolleybus lines with insulation on trolleybus wires and neutral disconnections where no energy transfer is possible. All the trolleybus overhead crossings are bi-directionally insulated. Also, the regenerative braking is not allowed on automated electrically-controlled overhead wire frogs, because the travelling direction is switched by high or low trolleybus load. The introduction of shared trolleybus, tram and bus operation on separate public transport lines increases the demand for a trolleybus autonomous traction with limited speed and distance to ensure fast removal of the vehicle from insulated intersections and other places where it can obstruct the traffic. The trolleybuses with built-in auxiliary diesel generator units with 100kW electric power are used on partially electrified routes Nr. 9 and 27, and for temporary route changes due to road-works and other reasons; however, a low-power generator increases the diesel oil consumption and reduces the vehicle acceleration, thus not allowing conversion of the bus lines with long non-electrified suburban sections to the duo-bus operation requiring continuation of using the bus under trolleybus wires in the city centre.

Even in the case of pure trolleybus operation, the requirement for modern trolleybus system performance is the continuous operation in the power shortage cases. Unlike heavy and light railway transport with a pantograph current-collection system the trolleybus double-pole current collection system is less reliable, since the former is able to dewire in the cases of overhead damages and inaccurate driving. In order to improve the passenger service quality and reduce the traffic delays, a modern trolleybus should have an ability to leave the insulated overhead crossing and unpowered track, drive around large obstacles and closed roads without external help. ESS installation is one of the least expensive and simplest ways to increase the trolleybus vehicle performance, especially for 60 technically prepared machines in Riga. Due to the more frequent trolleybus overhead voltage dropouts than in railway and tram networks, the ESS must provide the uninterrupted power supply in the case of overhead voltage failure by switching to autonomous traction mode without need to reset the traction and braking commands.

One of the most promising energy storage devices is a supercapacitor battery chosen for the trolleybus ESS. In comparison with chemical accumulator batteries and rotating flywheels, the supercapacitors have better charge and discharge dynamic characteristics despite the smaller total energy capacity. The advantage of supercapacitor is also independence of its parameters from the environment temperature. Supercapacitor ESS could be easily installed in the trolleybus rear equipment compartment instead of diesel generator auxiliary power supply. The trolleybus with a built-in diesel generator could be fitted with a supercapacitor ESS only if this latter could be installed on the roof.

The most attention has been paid to storing as much as possible regenerative energy, applying as simple as possible technical solutions, which would allow the least rise in the cost of traction equipment without decreasing the trolleybus operation safety. Such storage can be achieved using a single-stage pulse converter without intermediate DC conversions [7]. In this case the trolleybus power stage possesses two independent converters with pulse width modulators (PWM) for a trolleybus AC traction frequency converter and an ESS DC/DC current controller. As the ESS is connected to the filter capacitor of trolleybus traction converter DC bus, the interaction of the mentioned converter and ESS controller should be investigated in all driving modes. As distinct from DC traction drives, the conventional induction drive converter is continuously operating within the whole vehicle moving cycle even in the free-wheeling mode, which also increases the AC drive sensitivity to overhead voltage dropouts and fluctuations. Therefore, the possibility to compensate for the trolleybus drive input voltage fluctuations using the ESS is reviewed for the cases of temporary voltage loss and permanent loss of connection with the overhead in the driving and braking modes within the whole speed range.

The trolleybus operation in different starting and braking conditions has been simulated by PSIM and Matlab/Simulink for the overhead and autonomous traction modes. Stability of the trolleybus ESS control system's operation in the overhead voltage transient modes was studied for the cases of long-lasting voltage failures and short-term dropouts.

2. TROLLEYBUS AC TRACTION DRIVE WITH A SUPERCAPACITOR ESS

As shown in [7], a single-stage buck-and-boost DC/DC converter connected to the filter capacitor of a traction converter is the most economical solution for the on-board supercapacitor ESS. Such a converter provides controllable bidirectional power flow if the supercapacitor voltage is permanently less than that of DC bus. A power stage of the trolleybus AC traction drive with a supercapacitor ESS is shown in Fig. 1. The power stage consists of two main parts – a traction AC drive connected through the overhead network to a substation and a supercapacitor ESS. The single direction substation equipment without regenerative braking and any type of energy storage is common for urban transport and includes an uncontrollable diode rectifier.

The main parts of trolleybus AC traction drive are filter capacitor of traction converter C_f , traction converter $A1$ with the motor torque control and speed feedback and a 210 kW three-phase 20ML3550K/4 type traction induction motor. The ESS consists of 33.3 F supercapacitor battery C and single-stage buck-and-boost DC/DC converter $A2$ connected to the filter capacitor of traction converter

C_f . Unlike the fully independent control system of a tram ESS described in [8], the ESS control system of a trolleybus is connected to its control system for preventing false vehicle motion mode recognition and subsequent energy waste, battery discharge in the braking mode and charge in the traction mode instead of peak power shaving. The ESS converter charge-discharge mode switch uses the trolleybus driver's pedal signals in the driving and braking modes.

Fig. 1. The power stage of trolleybus AC traction drive with supercapacitor ESS.

For a 600 V overhead line with voltage deviations 450...780 V the supercapacitor voltage should not exceed 450V. The available ESS energy is calculated as

$$E_{ESS} = \frac{(V_{C_{max}}^2 - V_{C_{min}}^2)C}{2}, \quad (1)$$

and the braking power capability in the discharged state of ESS as

$$P_{ESSbr} = V_{C_{min}} I_{C_{max}}, \quad (2)$$

where: $V_{C_{max}}$, $V_{C_{min}}$ are the supercapacitor charge/discharge voltage limits,
 $I_{C_{max}}$ is the allowable supercapacitor current.

The 50 second factory test measurements of a fully loaded vehicle with the maximum acceleration and deceleration at a speed of 55 km/h have shown 126 kW braking power and 530 Wh regenerated energy. Such a power and energy capability provides a 33.3 F supercapacitor in the voltage range $V_{C_{max}} = 450$ V, $V_{C_{min}} = 290$ V, having $E_{ESS} = 547.6$ Wh. The ESS current at the start of braking does not exceed 435 A. The supercapacitor bank contains two parallel branches of 180 series-connected 3000F 2.7 V capacitors, so that the capacitor current is <220 A, which is available.

3. COMPUTER MODEL OF A TRACTION AC DRIVE WITH ESS

The traction AC converter of the trolleybus is simulated by a Matlab/Simulink direct torque control (DTC) drive model, and the supercapacitor ESS converter – by a PSIM-based continuous mode buck-and-boost converter substitution scheme [8]. The both models are joined by common SimCoupler software tool (see Figs. 2 and 3).

Fig. 2. Coupling of AC drive Simulink and ESS PSIM models.

In the simulation of ESS operation a simplified DTC induction drive model was used for a single trolleybus. Although the trolleybus has traction converter with a more complex control system (torque-controlled field-oriented vector control), the advantage of simplified model is the variable and increased inverter switching frequency, which allows the best possible investigation of traction converter instability and ESS converter joint operation in various power supply feeding modes.

The ESS PSIM model includes the models of feeding substation and overhead line (elements V_{sub} , $D1$, $R1$), filter choke L_f and the common for both converters filter capacitor C_f . The DC bus voltage transfer to the AC drive is made by voltage sensor $VSEN$ in the PSIM, and by controllable voltage source V_f in the Simulink. In turn, input current $I1$ of the AC drive converter is transferred to the PSIM model by current sensor $ISEN$ (Simulink) and the controllable current source $I1$ (PSIM).

The advantage of simulation software coupling is the possibility to use a brand-new continuous mode model of the PSIM-based ESS buck-and-boost converter [8] instead of the pulse model, developed to simplify and accelerate the simulation of ESS PWM converter [9]. The trolleybus ESS control system uses the well-approved supercapacitor charging algorithm [7, 9] with constant voltage V_f . For the ESS discharge mode the supercapacitor discharging algorithm [9] was modified by setting the discharge current proportional to the load current.

3.1. AC drive model

The trolleybus AC traction drive is replaced by Matlab/Simulink DTC drive model (Fig. 3).

The traction three-phase inverter DTC system is modified by adding to the motor load an aerodynamic drag torque block where drag and load characteristics are inserted, with speed feedback and enabling control loops added to the conventional DTC model. The speed feedback simulates the brake torque release at the trolleybus full stop even if the brake pedal is still kept pressed to prevent the

vehicle backward motion after the stop. The enabling signal blocks the drive mode in the autonomous traction mode if the ESS supercapacitor is discharged.

Fig. 3. AC drive Simulink model.

3.2. ESS model

The PSIM model of the installed on-board ESS is shown in Fig. 4. Voltage source V_{sub} and diode $D1$ relate to the feeding substation, and $R1$ is an equivalent resistance of the connecting cables and overhead line; R_{aux} is the equivalent load of trolleybus auxiliary equipment. The current source $ICCSI$ simulates the AC drive converter which is placed in Matlab/Simulink model (Figs. 2 and 3). Voltage source $VDC1 = 780$ V with diode $D2$ is the substitution for the filter capacitor's voltage limiter.

The switching mode buck-and-boost models of the ESS power converter are replaced with continuous ones [8] (subcircuit $S1$). This allows increasing the simulation time step and decreasing significantly the simulation time. Control signals D_1 and D_2 are continuous voltages limited in the range 0–1 V by voltage limiters $LIM6$ and $LIM7$. Their values are equal to the corresponding duty ratios for buck-and-boost converters in the switching mode model.

The ESS control system contains:

- charge controller of supercapacitor C ,
- discharge controller,
- supercapacitor voltage range limiter,
- charge/discharge mode switch,
- drive mode enabling switch.

For the ESS control purposes the following two voltages and two currents are measured: filter capacitor voltage V_f ($VSEN1$), supercapacitor voltage V_C ($VSEN2$), supercapacitor current I_C ($ISEN1$), and trolleybus AC drive converter current $I1$ ($ISEN2$).

The charge controller consists of voltage control loop ($VSEN1$, $LP2$, VV_{maxref} , $SUM1$, $PI1$, $LIM1$) and supercapacitor current control loop ($ISEN1$, VI_{maxref} , $SUM3$, $PI2$, $LIM2$). The voltage control loop stabilizes DC bus voltage V_f at a 750 V level providing transfer of the total braking energy to the supercapacitor [7, 9]. The second order low-pass filter $LP2$ with 700Hz cut-off frequency reduces ripple in the voltage control loop.

Fig. 4. PSIM model of ESS.

The current control loop is used for supercapacitor current limitation to an allowable value that is set to ± 700 A level ($V_{I_{maxref}}$) for both charging and discharging modes. Unit $S2$ connects the control loop with the smallest output voltage for feedback. If $I_C < I_{Cref}$, the output signal of $LIM2$ has the upper value, and the current control loop is disconnected. The voltage control loop is closed thus providing stabilization of voltage V_f . Similarly, in the current control mode $V_f > V_{fref}$, the output signal of $LIM1$ has the upper value, and the voltage control loop is disconnected. Both the feedback and feedforward for control signal $D1$ are implemented by elements $SUM2$, $DIVD1$ adding a small deviation d_1 to the steady state duty ratio D_{10} :

$$D_1 = D_{10} + d_1, \quad (3)$$

where $D_{10} = V_C / VV_{maxref}$,

$VV_{maxref}d_1$ is the output voltage of $S2$.

The discharge controller contains three control loops:

- current control loop ($ISEN2$, $LP1$, $ISEN1$, $SUM6$, $P2$, $LIM4$) – active in the drive mode and providing the supercapacitor discharge with the current proportional to that of AC drive measured by $ISEN2$. Low-pass filter $LP1$ helps to smooth signals, and $P1$ sets the coefficient of proportionality;

- voltage control loop ($VSEN1$, V_{fref} , $SUM7$, $PI4$, $LIM5$, $B5$, $SUM9$) – active in the autonomous traction mode (and in the cases of overhead voltage dropouts) and stabilizes the DC bus voltage V_f at a 550 V level set by V_{fref} . Differentiator $B5$ improves the dynamic characteristics and stability of the voltage feedback loop;
- current control loop ($ISEN1$, VI_{maxref} , $SUM4$, $PI3$ and $LIM3$) for supercapacitor current limitation is similar to that of the charge controller.

One of the three control loops is activated by elements $S3$ and $S4$, while the other two are disconnected.

In the ESS discharge mode the following equations for control signal D_2 are valid:

$$\begin{aligned} D_2 &= 1 - D_2', \\ D_2' &= D_{20} + d_2, \\ D_{20} &= V_C/V_f, \end{aligned} \tag{4}$$

where $V_f d_2$ is the output voltage of $S4$.

The supercapacitor voltage limiter consists of four voltage comparators $COMP2...COMP5$, two logic inverters $NOT7$, $NOT8$, two RS triggers $TRIG1$, $TRIG2$ and logic elements $AND5$, $AND6$. The charge mode is disabled when the supercapacitor voltage reaches 450 V, and is resumed when it falls down to 430 V. The discharge is disabled when this voltage falls down to 290 V, and is permitted again when it rises up to 310 V. The voltage limits are set by voltage sources $VD4...VD7$, correspondingly.

The charge/discharge mode switch uses the trolleybus drive and brake mode signals that are simulated in PSIM model by piece-wise linear voltage sources “run” and “brake”, correspondingly. The charge mode is enabled by closing switch $SS1$ and discharge mode – by closing $SS2$. Elements $AND5$, $AND6$, $NOT3$ and $NOT5$ prohibit the simultaneous activation of both modes.

The drive mode enabling signal is formed by means of elements $VSEN3$, $COMP1$, $VDC2$, $AND1$, $NOT1$, $NOT2$ and transferred to the Matlab/Simulink model via $SLINKn$. The enabling signal turns the reference torque to zero (in Matlab/Simulink model), in such a way blocking the trolleybus traction drive mode if the ESS supercapacitor is discharged and the overhead line voltage is below 450 V.

Electromagnetic torque and speed signals are transferred from Matlab/Simulink model to PSIM model for displaying them in Simwiew.

Parameters of PI controllers $PI1...PI4$, voltage limiters $LIM1...LIM5$ and other components have been optimized to provide stable operation of the ESS control system in different modes of trolleybus operation.

4. SIMULATION RESULTS

The PSIM-Matlab/Simulink simulations have been performed for single trolleybus starting and braking processes in the overhead line voltage feeding and autonomous traction modes. The following typical supply variants were simulated:

- conventional overhead voltage supply;
- autonomous traction in the case of overhead line voltage unavailability;

- permanent loss of overhead voltage (its unavailability up to a vehicle's full stop);
- temporary loss of overhead voltage (its unavailability for a short time).

First two supply modes are conventional for trolleybus traction. To prolong the autonomous traction mode distance without installing a more powerful ESS, the vehicle speed could be limited.

4.1. Trolleybus overhead and autonomous traction modes

Fig.5. Simulation results for the trolleybus overhead operation mode:
a) PSIM; b) Matlab/Simulink.

The simulation model suggests only a single vehicle's (independent of others) operation, assuming that its control system does not allow the energy distribution among many vehicles thus enlarging the available energy for catenary-free traction. To obtain the energy amount necessary in the cases of more frequent autonomous traction occurrence, the total trolleybus braking energy is stored in the ESS without transfer to other vehicles.

The shape of the trolleybus traction drive reference torque (Fig. 5) has been obtained in the 50-second factory test measurements for a fully loaded vehicle with the maximum acceleration and deceleration at a speed of 55 km/h. The trolleybus under test accelerated up to this speed from the start to 31.6 s and braked from 31.7 s to 46.4 s.

For simulation at the overhead feeding operation the substation voltage source V_{sub} was set to 600V. The ESS supercapacitor voltage V_C and current $I(C)$, substation voltage and current I_{sub} , filter capacitor voltage V_f and traction inverter input current I_I together with reference torque values are shown in Fig. 5a, while the speed, acceleration, induction motor stator current and electromagnetic torque characteristics – in Fig. 5b. Due to the peak shaving, the consumed substation current I_{sub} in the starting mode was reduced from 358 A to 125 A. In the braking mode, full ESS regeneration was provided.

In the autonomous mode of operation the trolleybus with ESS is disconnected from the overhead line by setting the voltage V_{sub} to zero. Simulation results for the trolleybus autonomous operation are shown in Fig. 6. The ESS converter's switching between the charging and discharging modes proceeds without unstable oscillations.

Fig. 6. PSIM simulation results for the trolleybus autonomous operation.

Due to the limited ESS capacity, the autonomous traction with the maximum traction current is possible within first 14.5 s, when the supercapacitor voltage drops close to the lower limit and the filter capacitor voltage decreases to 550 V. This forced switch-off point for the traction converter drive mode corresponds to a vehicle's speed of about 45 km/h.

4.2. Overhead voltage failure

Due to the pole-type current collector, a trolleybus can lose its power supply before the stop in the cases of accidental de-wiring or current collector remote lowering forced by driver. This latter is needed for bypassing large obstacles on the road and also allows switching to the autonomous mode without stopping the vehicle. Simulation has also been performed for overhead voltage failures at different stages of trolleybus movement. Figure 7 shows the case of overhead voltage failure occurrence at the 3rd second, when the trolleybus reached a low speed of 17 km/h at the start.

Fig. 7. Overhead voltage failure in the starting mode.

Fig. 8. Overhead voltage failure in the braking mode.

In the case shown in Fig. 7 the operation of trolleybus equipment is not disrupted, with only the maximum speed decrease from 55 to 47 km/h. This occurs because the undervoltage protection removes the reference torque due to the ESS supercapacitor discharging at 14.5 s. Figure 8 shows the overhead voltage failure in the regenerative braking mode. In this case the trolleybus starting process is not

different from that with overhead supply. It is seen that the voltage failure in the braking mode does not influence the traction stability.

4.3. Overhead voltage dropout

As compared with trams, the trolleybus power supply is prone to more frequent temporary voltage shortages owing to the overhead network and current collector design. The tram power supply system is made mainly without “dead” crossings, while trolleybus wires are insulated in crossings with not only trolleybus lines but also tram lines having long neutral sections. Most of widespread old generation Škoda 14Tr and 15Tr trolleybuses had a feature that the traction mode circuit was not reset by overhead voltage dropout if the driver pedal was pressed, and the trolleybus acceleration was resumed only after restoring the supply. Due to high sensitivity of the AC drive to the input voltage quality, such an operation mode is unavailable for modern trolleybuses which causes difficulties to operate them in the cases of heavy traffic at complex overhead intersections and increased substation load (e.g. at catenary’s icing). For improving the trolleybus traffic reliability, the ESS automatic switching to the autonomous traction mode is proposed. Such a solution has two operation cases during a supply voltage failure: a long-lasting dropout (at track crossings) and a short dropout (mainly caused by a vehicle’s passing the section insulator).

We have studied both the types: long (measured in a few tens of seconds, Fig. 9) and short (with 1 s duration, Fig. 10).

In the former case the starting mode is switched off due to the practically almost autonomous operation. The resumption of overhead supply voltage at the 25th second takes off the ESS discharge prohibition, thus allowing the automatic continuation of acceleration. The trolleybus traction equipment automatically switches between the overhead and the autonomous modes without oscillations. Frequent short-term overhead voltage dropouts (Fig. 10) do not cause speed-up interruptions. The trolleybus braking behaviour does not depend on the overhead voltage presence.

Fig. 9. Long overhead voltage dropouts in the whole speed range.

Fig. 10. Short overhead voltage dropouts in the whole speed range.

5. CONCLUSIONS

1. Simulation results show stability of the control system of the on-board ESS in all operation modes, and its ability to efficiently utilize the braking energy of a trolleybus.
2. Installation of a supercapacitor in the trolleybus with induction motor traction drive allows efficient storage of the total energy returned during the braking independently of the presence of other overhead-connected consumers.
3. The ESS provides the autonomous traction with the maximum speed of 45 km/h. To improve performance of the supercapacitor battery traction, the maximum speed limit in the autonomous mode can be reduced to 25–30 km/h.
4. The trolleybus drive system automatically switches to the supercapacitor battery in the case of overhead voltage shortage, ensuring continuous traction while the ESS discharges to the allowable limit. In the case of empty battery the traction mode is reset till the end of overhead voltage dropout (i.e. this mode restores automatically).
5. The induction drive system with automated switching to the autonomous traction mode can be used for elimination of braking losses and improvement of traction performance not only as applied to trolleybus operation but also in the subway and other rail transit systems when they have long catenary's neutral sections and instability of current collection.

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TROLEJBUSA ASINHRONĀS VILCES PIEDZIŅAS AR SUPERKONDENSATORU ENERĢIJAS UZKRĀJĒJU MODELĒŠANA

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Kopsavilkums

Rakstā apskatītas Škoda 24Tr tipa trolejbusa rekuperētās enerģijas saglabāšanas iespējas, uzstādot borta superkondensatoru enerģijas uzkrājēju ar automātisku pārslēgšanos uz autonomās vilces režīmu. Piedāvāta enerģijas uzkrājēja vadības sistēma ar konstantu DC kopnes spriegumu superkondensatora uzlādes režīmā un superkondensatora strāvu, proporcionālu vilces pārveidotāja strāvai superkondensatora izlādes režīmā. Izpētīta trolejbusa asinhronās piedziņas un enerģijas uzkrājēja vadības sistēmas stabilitāte gan īslaicīgos, gan ilgstošos tīkla sprieguma pazušanas režīmos. Sistēmas modelēšana veikta ar Matlab/Simulink asinhronās vilces piedziņas modeļa un PSIM enerģijas uzkrājēja modeļa apvienošanu vienotā sistēmā.

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