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Capacitive Energy Storage Device from Tram Auxiliary Power Supplies

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Professional paper

Voltage drops of the catenary supply on trams are very frequent, every 2 minutes on average for the city of Zagreb. Durations of the voltage drops vary from less than 1 ms to seconds. The tram air-conditioning units are fed from the catenary through power converters and are limited in the number of start/stop sequences per hour. They have to be powered with a kind of uninterruptible power supply. That way the operation continues with no interruptions during voltage drops. A solution with capacitive energy storage is chosen. Sizing of the capacitive tank and the working principle of the accompanying DC-DC converter are shown. Characteristics of the equipment are measured while operational. When the capacitive storage device is used, the air-conditioning unit works without interruptions during voltage drops of up to 320 ms. Majority of voltage drops are shorter in duration and the number of interruptions is limited to the level that guarantees reliable operation of the air-conditioning unit.

Key words: DC power supplies, capacitive energy storage, catenary supplies

1 INTRODUCTION

Capacitive energy storage devices are used in power supply devices and electromotor drives for number of reasons. Energy storage device is capable of covering shorter supply interruptions from main source [1]. Electric vehicles with such storage device are capable of passing shorter distances without catenary supply such as low height underground driveways or town squares. In case of supply interruption at catenary supply, underground rail is capable of reaching the next stop. It is also possible to construct passenger electric vehicles with no catenary supply. The energy is stored in energy storage device located in the vehicle at the stops, and it is sufficient to secure vehicle operation until the next stop. Such demands could be fulfilled by accu batteries as well, but in comparison to accu batteries; the new high capacitance capacitor technologies (supercapacitors) show significant advantages: no maintenance, considerably longer durability in relation to the same number of charge and discharge cycles, higher peak power, and little characteristic dependence with regards to the temperature [2]. If there is no need to have larger quantities of stored energy at disposale, then due to the aforementioned advantage of solution with supercapacitors, it is a better choice in comparison to the solution using accu batteries.

Energy storage device can be used to store the energy which in short time intervals is supplied from the load, and primary source is not capable of accepting it as it is the case with diode rectifiers. Typical use can be seen in electromotor drives. When the drive is brought to a standstill, the mechanical energy is converted into the electric energy and stored in order to be used for putting the drive into motion. Diesel-electric locomotive or tram fed from the catenary supply with diode rectifiers are such examples [3]. Fitting an additional device is justified if savings in energy consumptions are large enough to cover the costs of additional energy storage device. Electromotor drives for elevators are also examples where applying this kind of devices are justifiable [4].

Using capacitive storage device gives possibility to enhance the primary source supply quality because with this device it is possible to cover peak loads, respectively consumption surges which primary source can not support properly. In vehicles with hybrid drive, the implementation of supercapacitors along with chemical energy source is typical so the valuable attributes of both components are brought together: large quantity of stored energy and high peak power in short time intervals [5, 6]. In [7] the device with capacitor energy storage device for voltage drop compensation in catenary supply networks is described. At the ends of the network which are distant from the substations, due to the conduit lengths the voltage drops are pronounced. In case of heavier loads, there is a possibility for voltage to drop under the acceptable values. By fitting capacitive energy storage device at such points it is possible to elevate the voltage at peak loads. Advantage in relation to mounting new traction substations is the fact that there is no need for creating a new electric connection from the distribution network.

Capacitive energy storage device, when created as a single device, in general consists of capacitor battery and bidirectional static converter [8, 9]. The static converter serves to limit, respectively to regulate charge/discharge capacitor battery currents. The static converter can also maintain a constant voltage at the device output during capacitor battery discharge [1, 2, 6].

This paper describes the capacitive energy storage device which is currently being fitted in TMK2200 series trams in Zagreb. The capacitive storage device serves to ensure uninterrupted operation of AC auxiliary loads which are fed from converters for auxiliary supply. The device consists of capacitor battery as an energy storage device and DC converter with bidirectional energy flow. In Chapter 2 there is a description of the main characteristics of the catenary supply net for the Zagreb electric tram as primary source and characteristics of auxiliary loads in TMK2200 series tram. The result of this is a need to search for a solution which will enable uninterrupted operation of load. In Chapter 3 the choice of energy storage device solution is described. Chapters 4 and 5 describe both sizing and operation of capacitive storage device, as well as results of measurements in operation.

2 PARTICULARS OF TRAM AUXILLIARY LOADS SUPPLY

2.1 Characteristics of the Zagreb electric tram catenary supply network

Nominal voltage of the Zagreb electric tram catenary supply network is 600 V DC with voltage variations from –30 % to +20 %. The network consists of 40 electrically separated sections. The sections on catenary supply are separated by section switches – insulated pieces of 0.5 m in length. Average length of catenary supply between section switches is 500 m [10]. When tram passes over the section switch a brief supply interruption occurs. If we take into consideration that the maximum tram speed while passing the section switch

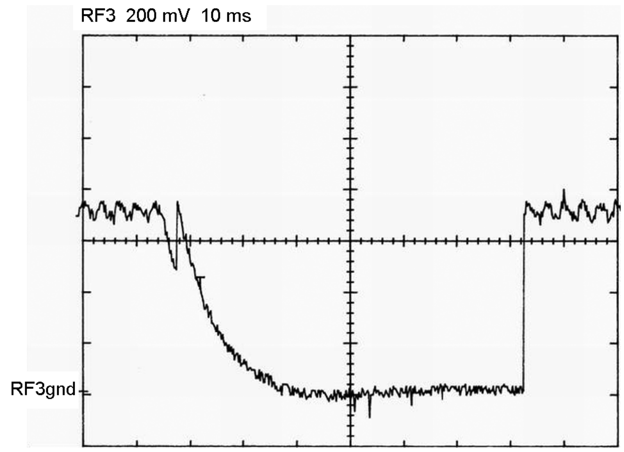

Fig. 1 Oscillogram of catenary supply voltage recorded in tram while passing over the section switch. Voltage axis: 180 V/div., time axis: 10 ms/div

is limited to 54 km/h, the supply interruption while passing the section switch lasts 33 ms as a minimum. In reality this time can be somewhat shorter because the electric arch occurs when pantograph leaves the part of catenary supply under voltage so the current continues to flow until the electric arch disappears. The longest duration of interruption will depend on minimal speed that the tram is moving over the section switch. In reality, as it has been demonstrated by the results of measurements in this paper, the longest periods rarely exceed 400 ms. In Figure 1 there is a characteristic oscillogram of catenary supply voltage recorded in tram while passing over the section switch. Oscillogram was recorded in TMK300 series tram while in traffic. In about 20 ms the voltage drops to 0 V. The duration of time interval where the voltage was below 400 V in the demonstrated case is 63 ms.

During regular operation of the tram supply interruptions occur also when the tram approaches a railroad switch. For the purpose of managing the railroads switch from the tram in safe manner; all loads in the tram are switched off for a moment. This lasts about 3 s. Voltage drop below limit values also occurs in transitional events due to heavy load (putting tram into motion). Duration of these drops is under 10 ms. These transitional occurances also include voltage surpasses so the voltage can reach a peak value of approximately 1000 V at average value of 650 V [10]. When pantograph bounces the transitional events occur along with supply drops which last about 10 ms. If we limit the observation only to the section switches, the frequency of interruptions in regular operation can be evaluated from estimated average speed of tram in Zagreb which is around 14 km/h and average distance between the section switches which is 500 m. Supply interruptions caused by passing over section switches occure on average every 2 minutes. To all of these, interruptions caused by railroad switches as well as other transitional occurances must be added, so the number of interruptions during regular operation exceeds 30 per hour.

2.2 Supply of auxiliary loads in TMK2200 series tram

All auxiliary AC loads in the tram are fed from the catenary supply net via auxiliary supply converter. Figure 2 shows basic block scheme of the converter for the supply of auxiliary AC loads. Input DC converter in the DC link capacitor C_d gives stable DC voltage of U_{dn} = 580 V and galvanically separates the DC link from the input. Output converter gives at its output a pulsewidth modulated three-phase voltage of 3 × 400 V which is additionally filtered by sinus filter. Total power of connected AC loads at output is 20 kVA. All loads are asynchronous motors with cosφ of approximately 0.8 so the transferred active power is 16 kW.

AC load with the largest consumption is air-conditioning unit with asynchronous motors which are used to drive fans and compressors. Number of switching on air-conditioning units due to compressor construction is limited to maximum of 15 per hour, and for the purpose of achieving higher level of reliability, it is recommended to keep this number as low as possible. When supply interruption from the catenary supply occurs, the AC converter can continue to work until the DC link capacitor is discharged to a certain level. Air-conditioning unit switches off when the supply voltage drops under 90 % of nominal voltage, respectively 360 V. In applied PWM modulation the alternating output voltage drops below 360 V when the DC link voltage drops below approximately 520 V. The capacity of DC link capacitor C_d is as high to allow the voltage to drop from 580 V to 520 V with constant power of discharge of 16 kW in approximately 10 ms. Each supply interruption from the catenary supply lasting longer than 10 ms shall consequently mean switching off of the load and a new switching-on sequence after repowering from the catenary supply. As it is clear that these interruptions lasting longer than 10 ms during regular operation will be on average more than 30 per hour, such operation is unacceptable. Enlargement of DC link capacitor battery leads to unjustifiably large capacitor battery inside the converter because a multiple capacity enlargement would be needed and consequently a proportional enlargement of both volume and weight of the capacitor battery. It is necessary to choose a solution which at the same time will be more efficient and will not interfeere with auxiliary supply converter operation.

3 SELECTION AND CONCEPT OF SOLUTION

One of the possible solutions for uninterrupted supply (for short time intervals) is shifting the main tram drive from motor to generator operation. When there is a voltage drop on catenary supply which is below certain level, the main drive should shift to generator regime in order to maintain a constant voltage U_{ul} at input (input voltage in the tram). This way all of the auxilliary loads would continue to operate. The energy would be taken from the tram kinetic energy. A brief slowing down of the tram would occur which could impact driving confort, mostly because of abrupt occurance of braking power and not so much because of the amount. It has been estimated taking into consideration the mass of partially loaded tram of 50 t, with speed of 8 m/s and 50 kW consuption of all tram loads that the deceleration of approximately 0.5 m/s^2 is necessary. The slowing down shoud be achieved in 10 ms from the moment of voltage interruption in order to quickly establish necessary energy flow from tram mass, so the voltage drop seen by the auxiliary loads would not last longer than 10 ms. Under the assumption that the drive dynamics allows such fast changes, there would be a change

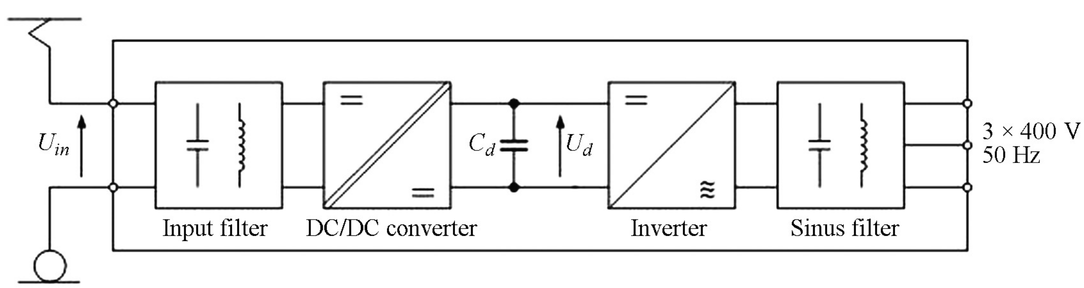

Fig. 2 Block scheme of the converter for the supply of auxiliary AC loads in TMK2200 series tram

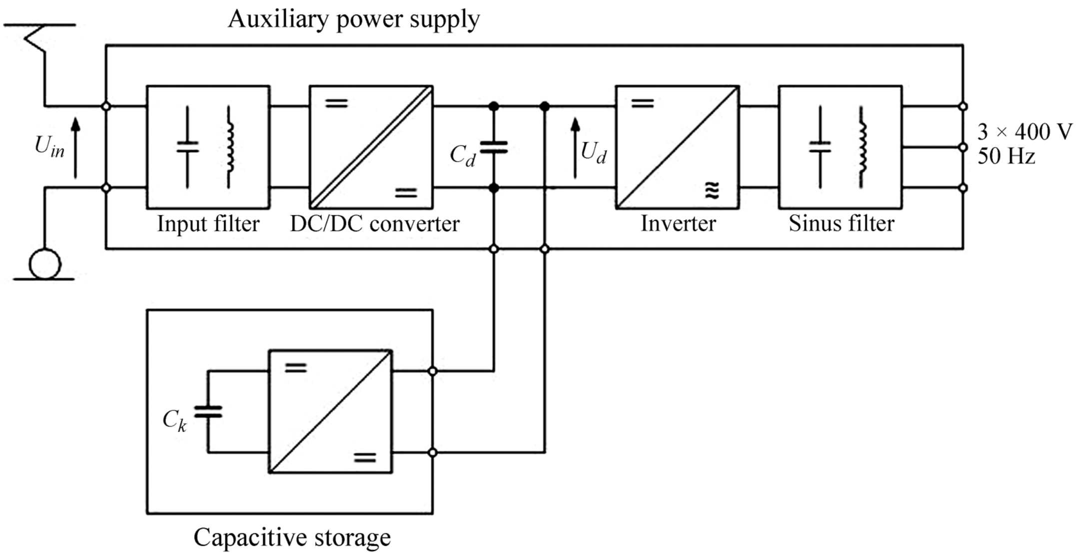

Fig. 3 Block scheme of the auxiliary supply with capacitive energy storage device

in deceleration of 50 m/s^3 which is far above emergency acceptable level of 8 m/s^3 while it is considered that in order to maintain the confort of the drive, those values shoud not exceed 1.5 m/s^3 [11]. In light of these arguments it has been selected a solution with separate energy storage device, independent of main drive.

As the energy storage device a capacitor battery has been selected because of simplicity and availability. Figure 3 shows block scheme of the auxiliary supply with capacitive energy storage device. Capacitive battery along with DC converter creates a separate device.

In case of the catenary supply with less number of section switches and contactless railroad switches, due to less number of interruptions, the capacitive energy storage device would not be necessary. The auxiliary supply converter then operates without this additional unit.

Capacitive energy storage device is connected to DC link and not to the input of the converter. This solution is more convenient for more reasons. In DC converter it is possible to use 1200 V semiconductor switches while at the input of the auxiliary converter (catenary supply voltage) it is necessary to have semiconductor switches of 1700 V because of unstabilized voltage. Furthermore, proper place for detecting drop is the DC link, respectively at the input of the output inverter itself.

DC converter of the storage device is constructed as a chopper with bidirectional energy flow, Figure 4. During the discharge of the capacitor battery C_k switch S_1 and diode D_2 do not conduct, and the S_2 switch is driven in a way that the converter acts as a boost chopper and at the output of the converter (connection to DC link) the constant voltage U_d is maintained. During the capacitor battery charging S_2 switch and D_1 diode do not con-

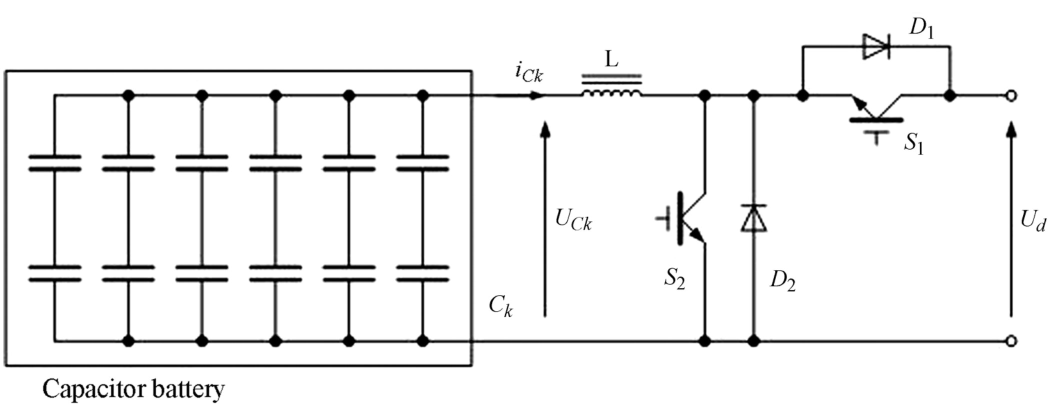

Fig. 4 Schematic of the DC converter energy storage device together with capacitive battery

duct, and S_1 switch is driven in a way that the capacitive charging current is limited.

The basic purpose of the DC converter is a possibility to utilize larger portion of the capacitor battery C_k stored energy. If we presume only capacitor battery with C_k capacity without DC converter, with disappearance of catenary supply voltage the capacitor battery starts to discharge from the initial voltage U_{dn} with the output converter current which continues to operate. After the battery is discharged to 0.9 U_{dn} the converter seizes to operate. Transferred energy W_k from the capacitor is:

$$W_k = \left[U_{dn}^2 - (0.9\,U_{dn})^2\right] \cdot \frac{C_k}{2}. \qquad (1)$$

With DC converter, capacitor battery C_k can be discharged even below the value of 0.9 U_{dn} because the capacitive storage device converter is capable of maintaining the constant voltage in the DC link in the limits of $0.9\,U_{dn} < U_d < U_{dn}$. If the constant power is tranferred to the DC link, as the voltage on C_k drops, the discharge current of the battery C_k rises. The nomunal current of semiconductor valves S_2 and D_1 is chosen in a way that the discharge current of the capacitive battery C_k can have the value of up to 120 A. If the given power of 16 kW is then transferred with ommited losses in the converter, the lowest voltage of the capacitive battery can be 133 V, respectively 0.23 U_{dn}. Now the transferred energy W_{ipk} is:

$$W_{ipk} = \left[U_{dn}^2 - (0.23\,U_{dn})^2\right] \cdot \frac{C_k}{2}. \qquad (2)$$

Energy ratio according to the terms (1) and (2) is

$$\frac{1-0.9^2}{1-0.23^2} = 0.20$$

which means that by using DC converter it is possible to utilize significantly more energy from the capacitor, in this case 5 times more in comparison to what could have been done without DC converter, or for the given quantity of usable stored energy we need 5 times smaller capacitive battery.

DC converter of the storage device, in addition to maintaining constant voltage of the DC link during the discharge cycle, during the operation on catenary supply it also limits the charging current of the capacitor battery C_k. As the average times between discharging cycles are around 2 minutes, it is enough to choose low charging current which will allow for the battery C_k within that time frame to get charged to the full value of voltage U_{dn}. According to the previous estimates, it is enough for the charging current from the DC link to have the value of 5 % of the nominal current of full load so the charging time is below 1 minute. It is enough to perform the electrical sizing of the auxiliary supply DC converter to operate on nominal load power because during the charge of the capacitive battery the output current does not increase significantly.

Additional advantage of the presented connection of the capacitive energy storage device and auxiliary supply converter is evident in case of heavy loading such as starting an asynchronious motor by directly connecting it to the converter output in operation. In supply of required energy in transitional occurance the capacitor battery is engaged via diode D_1. Additional capacity is regularly higher by several times than the DC link capacity so the inevitable voltage drop of the DC link at load surge is considerably lower in comparison to what it could be without the energy storage device.

4 ENERGY STORAGE DEVICE SIZING

In order to get a more accurate picture of number and types of voltage interruptions, there have been taken voltage measurements of catenary supply in operation on existing TMK300 series tram. The voltage of the catenary supply was measured countinously in operation with measuring LV100 voltage converter LEM in traffic. Measurement lasted 2 hours and 48 minutes. The results obtained have been stored in Dewe 2010 measuring centre. It was chosen a representative section in Zagreb network from origin point Ljubljanica to destination point Dubec with most section switches and railroad switches. Time period selected for the testing was between morning and afternoon peak hours when it was possible to achieve higher average speeds of driving in actual traffic in order to get a picture of worse case scenario (higher number of interruptions per time unit), but still realistic. As the voltage interruption it was taken a voltage drop below 400 V which lasted longer than 10 ms. In these conditions it was recorded 109 voltage drops in the specified time frame lasting 2 hours and 48 minutes which gives around 39 drops per hour. Causes for these occurancies were identified as 33 passings over railroad switches, 71 passings over section switches and in 5 cases the most probable cause was a pantograph bounce.

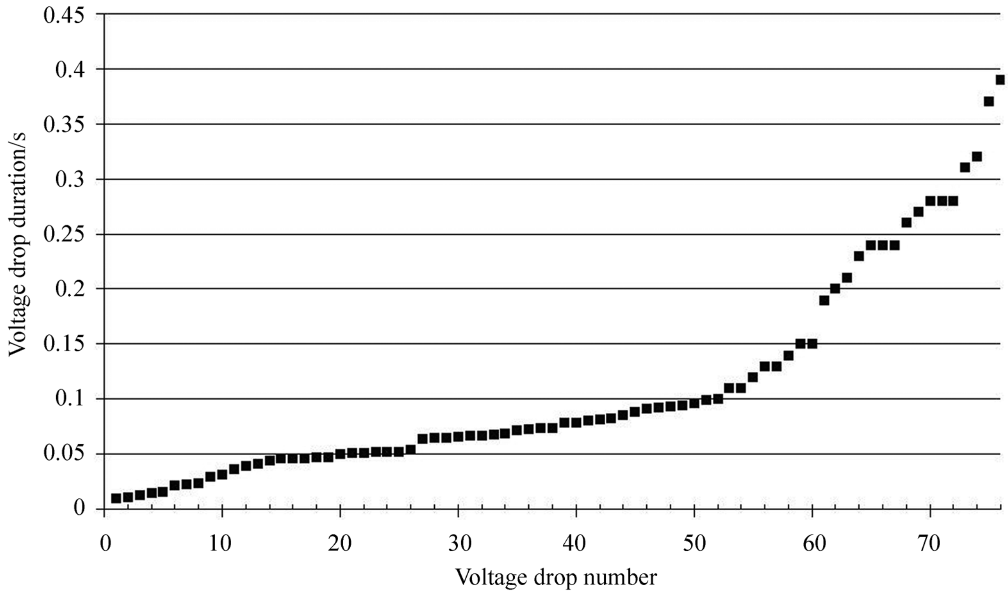

Fig. 5 Measured voltage drop durations longer than 10 ms aligned according to increasing values. Drops caused by railroad switches are not shown

Duration of the interruptions in case of passing over railroad switch was between 2 and 4 s, while duration of the rest of interruptions was below 0.4 s. Previous estimate led to the conclusion that covering drops caused by passing railroad switch was not justified as it lasted too long and there was too high demand for capacitive battery in the storage device. If all the other drops would have been covered, considering those measurements as relevant, no more than 12 drops per hour would remain, which is acceptable.

The chart in Figure 5 shows durations of all measured drops without drops caused by railroad switches aligned according to increasing values. Average drop duration is 0.11 s, and only 2 drops last longer than 0.35 s.

In accordance with these results a total capacity of storage device capacitor battery of 36 mF was selected so according to (2), the energy available is 5735 J, and respectively it is possible to cover the total consumption of 16 kW lasting 0.358 s. As the air-conditioning unit, observed through longer period of time, on average does not load the converter with its full power (winter period), in most cases it will be possible to cover even longer intervals without supply. It has been estimated that with the selected energy storage device all the drops, except the drops caused by passing over railroad switches and neglectibly small number of passings over section switches, were in reality covered.

5 CONSTRUCION OF CAPACITIVE STORAGE DEVICE AND MEASUREMENT RESULTS

Figure 6 shows a photograpfy of constructed capacitive energy storage device type KBT which is being fitted in new TMK2200 series trams without upper cover lid. Capacitor battery is connected by serial-parallel connection of 12 electrolytic capacitors of 350 V and 12 mF. Equivalent capacity is 36 mF.

In such devices supercapacitors are most often used, but for the voltage of 580 V and relatively small capacity required as it is in this case, the use of supercapacitor is not justified. Supercapacitors have several time better ratio of stored energy and weight in relation to electrolytic capacitors, but nominal voltage of one unit is 2.5 V so it is necessary to have a large number of serially connected capacitors with additional circuits for voltage equilization [7]. Weight of electrolytic capacitors in constructed energy storage device equals 25 % of total device weight so that even considerable reduction in capacitor weight does not mean considerable reduction in total device weight.

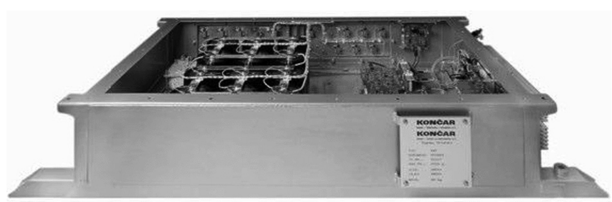

Fig. 6 Capacitive energy storage device type KBT

Storage device DC converter is constructed with 1200 V IGBTs. The device is intended to be mounted on tram roof, it cools naturally and the casing is closed in IP55 class protection.

Energy storage device is not regulated from the auxiliary supply converter nor from the superior tram system but the storage device operates completely automatically. The device has its own autonomous regulator and protection circuits. When the DC link voltage drops below 95 % of nominal value, the voltage regulator of energy storage device activates and attempts to maintain the DC link voltage so it gives required current from the capacitor of the storage device to the DC link until the capacitor battery current increases to the level of current limit adjusted to 120 A. Capacitor battery can continue to discharge, but now the DC link voltage drops as well. When all the energy gets consumed, the current stops flowing. When the catenary supply voltage gets restored, the DC/DC converter restors full DC link voltage. Voltage regulator of storage device is blocked because the DC link voltage value is now higher than the adjusted value. Current flow from the DC link to empty capacitive battery of the storage device is restored. This current is limited by the current regulator in the storage device. When the DC link voltage and capacitive battery voltage are equal, the current naturally stops flowing. Detailed review of the regulation algorithm is showed in [1].

Operation during discharge of the capacitive battery is illustrated by oscillograms in Figures 7 and 8. The oscillograms were recorded in laboratory, but with all real components of auxiliary suplly used in tram. Described energy storage device KBT type is connected to auxiliary supply converter and the auxiliary supply converter itself is loaded with air-conditioning unit just as it is in the tram. External circuit devices in the supply source simulated input voltage drop with adjustable duration period. Figure 7 shows oscillograms of DC link voltage U_d and storage device capacitor battery voltage U_{Ck} (designations according to Figure 4) during input voltage drop. Voltage drop lasts around 0.36 s, and auxiliary converter is loaded at the output with active power of 14 kW. At the beginning the DC link voltage drops from nominal 580 V to 540 V, as that is the adjusted value in storage device voltage regulator. After that the capacitive battery gives energy to DC link and its voltage drops, but in the DC link it is still maintained at constant 540 V which is enough to ensure operation of inverter and connected AC loads. After 0.36 s of discharge the capacitive battery voltage dropped to 200 V. At that moment the input voltage is restored; DC/DC converter of auxiliary converter raises the DC link voltage to 580 V and continues to regulate the operation while the capacitor battery of the storage device is charged with slow voltage raise. Oscillogram in Figure 8 shows an example with the same load, but the drop lasts around 0.45 s which causes a complete discharge of the capacitor battery. Both voltage and current of the capacitor battery are shown. As the voltage drops, so the discharge current raises in accordance with constant power which is transferred to DC link up to approximatelly 0.38 s from the beginning of the drop. At that moment occurs limitation

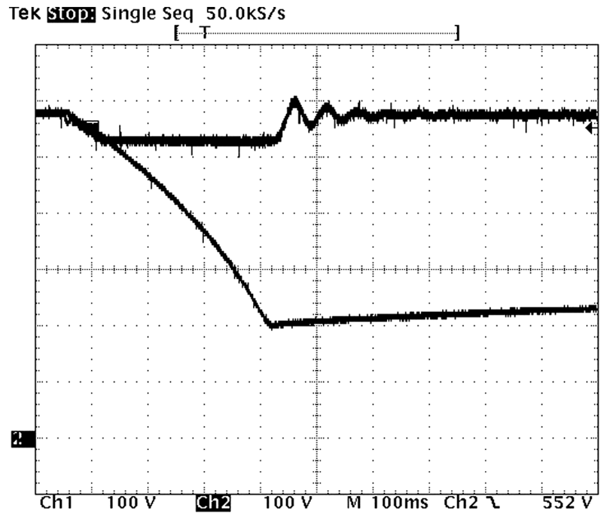

Fig. 7 Oscillograms of DC link voltage U_d and storage device capacitive battery voltage U_{Ck} during input voltage drop U_{ul}. Channel 1 and channel 2: 100 V/div, time axis: 100 ms/div

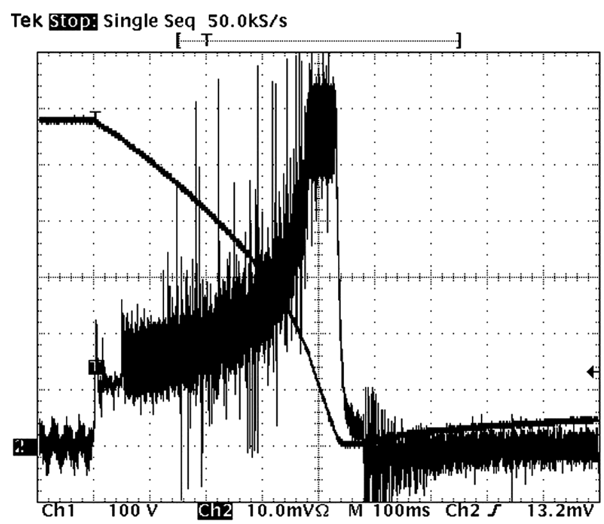

Fig. 8 Oscillogram of capacitive battery voltage U_{Ck} and capacitive battery current i_{Ck} during input voltage drop U_{in}. Channel 1: 100 V/div, channel 2: 20 A/div, time axis: 100 ms/div

of discharge current at approximately 110 A which was adjusted in regulator. Capacitive battery discharges completely to 0 V taking into consideration that the constant voltage in AC link can no longer be maintained.

Funcionality testing was performed also on the tram in real traffic. During the passing over section switches the AC loads continue to operate. Duration of drops which is possible to overcome without outage is consistent with the load according to equation (2).

6 CONCLUSION

Adding a relatively simple and reliable device to the auxiliary supply system of the TMK2200 series tram leads to a solution of a large number of supply voltage drops which is characteristic for the Zagreb tram network. Systematic survey of real number of interruptions over a longer period of time has not been performed, but based on measurement undertaken in shorter period of time it can be estimated that by adding the above described energy storage device the number of outages was reduced for more than 3 times (39 outages per hour in comparison to 12 outages per hour) which guarantees acceptable and reliable operation of the loads. The first fitted devices have been operational without any malfunction for over two years and through regular air-conditioning unit maintenance it has not been noted degradation of relevant characteristics.

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Kapacitivni spremnik energije za pomoćna napajanja tramvaja. Kod napajanja potrošača na tramvaju iz kontaktnog voda vrlo su česti prekidi, u prosjeku svake dvije minute za Zagreb. Više je razloga zbog kojih dolazi do propada u naponu napajanja koji variraju u trajanju ispod 1 ms pa do nekoliko sekundi. Klimatski uređaj se napaja iz kontaktnog voda preko pretvarača, a ima ograničen broj zaustavljanja/pokretanja u jedinici vremena pa je potrebno osigurati napajanje, odnosno besprekidan rad i za vrijeme prekida dotoka energije iz kontaktnog voda. Odabrano je rješenje s kapacitivnim spremnikom energije. Prikazan je odabir rješenja, princip rada i dimenzioniranje spremnika energije. Ispitane su karakteristike spremnika energije u pogonu. Spremnik energije pokriva propade u napajanju od približno 320 ms kod pune snage potrošača što u praksi čini veliku većinu prekida napajanja. Klimatski uređaj u stvarnom pogonu radi s vrlo malim brojem zaustavljanja koji je unutar dopuštenih granica.

Ključne riječi: istosmjerni pretvarač, kapacitivni spremnik energije, kontaktni vod

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