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«Использование гибридных накопителей энергии в электроприводе трамвая (г.Прага)» «Use of alternative power source as hybrid drive for tramway in Prague tramway lines»

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Реферат

Выпускная квалификационная работа 107 с.,31 рис., 24 граф., 10 табл. , 16 источников

Ключевые слова: трамвайная сеть, накопители энергии, суперконденсаторы, аккумуляторные батареи.

Обьектом исследования является использование накопителей энергии в тяговом электроприводе трамвая XXXX в городе Праге

Цель работы – определить возможность модернизации трамвая XXXX путем добавления гибридного накопителя энергии в тяговый электропривод для повышения его энергетической эффективности.

Методы исследования – аналитический, проектный, компьютерное моделирование.

В процессе исследований проведен аналитический обзор повышения эффективности тягового электропривода трамвая путем рекуперации энергии. В качестве накопителя энергии рассмотрены варианты его построения на суперконденсаторах, аккумуляторных батареях и гибридного типа. Разработаны математические модели динамики трамвая, силового преобразователя и накопителя. Определена оптимальная емкость накопителя. Проведено технико-экономическое обоснование.

В результате исследования определена целесообразность применения накопителей энергии в системе тягового электропривода трамвая.

Степень внедрения: Резултаты расчетов могут быть использованы при работах, связанных с модернизацией трамвайного парка.

Область применения: Городская трамвайная сеть

Экономическая эффективность/ значимость работы: Полученные результаты позволяют уменьшить потребление энергии в городской трамвайной сети и сократить протяженность контактных линий.

В будущем планируется: Проведение уточненных расчетов с учетом оценки движения и циклов заряда-разряда накопителя на больших временных интервалах.

Abbreviations

APS- Alternative power sources

DPP- Prague transport service company (Dopravni podnik Praha, a.s.)

EDB- electrodynamic brake

EV – electric vehicle

HV- high voltage

LTO - Lithium Titanate ($Li_4Ti_5O_{12}$)

MG- motor-generator

NCA - Lithium Nickel Cobalt Aluminium Oxide ($LiNiCoAlO_2$)

NMC - Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$)

PCC- Presidents´ Commerce Committee

pF – piko-Farad ($1pF = 1 * 10^{-9}$ F)

PRE – Prague supplier energetic company (Prazska energetika, a.s.)

Supercap – supercapacitor shortcut

TRAM- tramway

µF – micro Farad ($1\mu F = 1 * 10^{-6}$ F)

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Introduction

We, as citizens living in 21^{th} century, are surrounded with modern technologies in all parts of our life. Modern trends in technologies are ecology, economy and energy savings. This topic affect not only our households or free time technologies but as well work accessories or transport technologies. In developed society is the necessity of fast, save and ecologic transport. And of course from one day to another more important.

This master thesis is set as case study based on research of possibility of using alternative power source as accumulator in Prague tramway lines. As this case study will show, there are many possibilities how to use any alternative power sources in Prague tram lines such as flywheels, fuel cells, supercapacitors, batteries or hybrid system consist supercapacitors and batteries in one device. For this research is used only three types of researched technologies and that are standalone supercapacitors, standalone batteries or hybrid system consist both technologies.

First part of the work consist history of tramway transport in Prague that is really rich. Prague, as capital, use tramway lines for more than 140 years and due to fact that Prague had for a long time some famous name´s mechanical engineering manufactures such as Ringhoffer, Tatra or CKD companies, there was a possibility to test new technologies in the city.

Part about history slightly turns into technical preview of mostly common types of trams used in Prague in history, present and introduction to some technologies used in Prague in the future. If we mention city name “Prague” most people will remember Charles bridge or Prague Castle, but people with target into technics mostly will remember about world tram legend Tatra T3. Case study´s list contains not only this type of vehicle but tramways used before as Ringhoffer´s tram, but as well modern and still manufactured tramways type 15T and 15T4, which were designed especially for Prague tramway lines.

The most important part is part based on technical solution of using alternative power sources in chosen tramway. As most important thing was to choose the tramway line, that is not only flat. It means to find a tramway line where up-hill and down-hill parts are, where the vehicle can store some energy into APS system and where this energy could be used. As the most appropriate was chosen the tram line No.1 that rides from Sidliste Petriny to Spojovaci tram stop. Calculations are done for explanation only in one way ride. On the way back there are differences in distances between tramway stops, in altitude between tramway stops that mean the power and energies used or saved to system could be different. However, the calculation programme that is evaluated in Matlab Simulink is possible to calculate any other track if we are able to insert all the information about distances between tram stops and altitudes. The results of used energies and energies that we can store helped me to calculate capacity of storage system and features used in this storage system.

Every technical issue, with a main goal of quality, must have as well economic calculations of expedience. These calculations will show better if the technical solution is possible to realize or not and what conditions could be accepted in case of realizing due to fact of having benefits from this solution.

In this master thesis were used technologies of Matlab Simulink, Microsoft Office Excel and Word. All the files containing the model, track information or economic calculations is possible to download from CD-disk inserted in this work.

1. History and present of tramway system in Prague

Modern trends in city transport are to use more comfortable and more ecological transport like underground or trams are. The idea of using railway tracks in city was firstly mentioned in 19.century. Even when we are talking especially about Prague, the first city railway system was used on 23. September 1875 like a horse-drawn tramway. It contained horse and a carriage. It was financed and built by Belgian entrepreneur Edouard Otlet. First line in the city was built from city part „Karlin“ to „Narodni trida“. The growing of horse-drawn tramway network was quick. Few years after, exactly in year 1883, had the horse-tram network in Prague about 20 kilometres of tracks. For the late 70´s of 19th century there were some experiments to change horse for electricity. Then in 1880 was first time introduced first electric tramway in Sestroretsk near Saint Petersburg. It worked without any problems and in any weather, so after example of Saint Petersburg followed the idea of electric tramways other cities in Europe like Berlin, Vienna, Brighton and in year 1891 also Prague. The person who was associated with electrification of Prague railway system was Frantisek Krizik. Who was constructer of first Prague electric tram in Austria- Hungary. Voltage of this tram was set to 600V direct and plus pole was wire above the earth and negative pole was a railway track. Actually, in the beginning it was not so common with electric trams. Firstly there were more ideas about how could be powered tram in Prague. But in the competition with steam tramway, horse-drawn tramway, gas tramway and ride tramway (Special invention of Czech constructer Sylvester Krnka, where was places for 20 people who ride it exactly like a bicycle. During the age of view for economic and ecological transport we can say, that invention of ride tramway could be still possible to realize.)[1]

After Krizik´s electric tramway beat all the other ideas, the growing of electric network for city transport started grow rapidly. In my opinion, the decision of using electric tramways helped to grow also electric power system in Prague.

In 20th century there were two periods when the tramway city transport in Prague was threaten with closing. It was during World War I and II and in 60´s and 70´s when the underground build-up started. Some of the lines was closed because they have the same way as a new build underground line. From the early 80´s until today are city tramway lines growing again. Totally different type of car was firstly tested in 1985 and it was type KT8D5.It was the first tramway, which had door on both sides of it. After changed political situation in 1989 came first cars in years 1991-1992. It´s type T6A5. These vehicles are still in service but all of them are reconstructed and there were developed some hacks and newer technologies on them. Another new vehicles came in year 2005 and it was type 14T. These trams are first new low-floor vehicles from Skoda Transportation and totally was built 60 pieces. Actually there are now in service only 4 pieces. This is caused by few failures in construction. After time these trams were put into service in Prague, designers realized that this vehicle is not appropriate for Prague tram network which contains a lot of curves and hills. This failure caused many problems with structure and consistency of boogies and vehicle´s main frame. This situation didn´t help as well many reclamations from passengers side about seating features in front and end part of vehicle, where were seats on opposite sides and it was really uncomfortable to sit during ride.

During these days are all the oldest vehicles changed for new one 15T type that are produced by Skoda Transportation. During years 2009-2015 was built and put into operation 125 pieces of 15T trams. According to contract between years 2015-2018 will Skoda build more 125 trams of modernised type 15T4 with edited control system, less plastic parts for easier repair in case of accident, added air-condition and wireless internet system. To the future is planned completely change older types of tramways like T3 or T6A5 with low-floor 15T and 15T4.

2. Most known tramways used in Prague

2.1. Ringhoffer tram

Ringhoffer factory was one of the biggest in Prague in 19th century and until time it was nationalized and set up part of Tatra Smichov Company. Their manufacturing portfolio consists except tram, passenger carriages, locomotive tenders and steam boilers. Company built all carriages for horse-drawn tramways and in 1897 also first electric tram in Prague. In early 20´s of 20th century, there were all trams in Prague supplied by electricity.

Model of Ringhoffer´s tram (Picture 3) was revolution in Prague. It consisted MVB 35 traction motors designed by another Czech great inventor Frantisek Krizik. This device had an output of 26 kW, which was more efficient and powerful than horse-drawn tram. This tram consist few important parts for its properly work. That are resistor boxes, controller, brakes and safety system.

Resistor boxes are hidden under supporting frame in the middle of TRAM (Picture 2). Inside of these resistor boxes are resistance plates, which main task is to downgrade voltage coming to DC engines. Main principle of this regulation is to change electrical energy into heat. This method was used in next types of Tatra trams T1,T2 and T3. This part is heart of regulation and it´s important for acceleration and motor braking.

Driving this TRAM was really easy so as traction circuits. TRAM was driven with one controller (Picture 1), through resistors for drive and braking and in dependence of wished state of drive or brake driver went up or down to bigger or smaller resistance with handle to wished degrees on the panel. There are 7 degree steps on controller for driving. The biggest resistance we can measure on the first step. Between 4th and 5th step is resistor box mostly cut and DC motors are in series. Last step, the 7th, is when voltage on DC motor coming directly from wires. During braking, the circuit is in same construction except of changing magnetic field in DC motor for changing direction of rotating magnetic field.

Except of electrodynamic brake this tram consists as well mechanical brake based on frictional force from breaking block on rotating wheel. As part of safety systems is installed plough, which fall down few centimetres above rails to clean up rails from any object which could cause an accident.[2]

Picture 1 - Ringhoffer TRAM´s controller panel with resistors (Illustrating picture) author: Daniel Sihlovec

Picture 2 - Resistor boxes on Ringhoffer tram (photo: Josef Rozsypal)

Picture 3 - Historical Ringhoffer tram in Prague (Photo: Michael Taylor)

2.2. Tatra T1

After World War II was in Prague totally different political situation. Ringhoffer´s factory was nationalized and grouped with name Ringhoffer-Tatra Smichov (later only Tatra Smichov). Main task of this manufacture was to develop and build new type of TRAM which would have only one driver station and will be done in the base of new American concept „*Presidents´ Conference Committee*“ (PCC) which was firstly based in USA before World War II. First type of PCC tram in Czechoslovakia was tram T1 made by Tatra Smichov (Picture 4) in 1951 and premiere drive was on 22.1.1951 in Prague. Between years 1952 and 1958 was build 287 of these trams. Mostly these trams were used in Prague but also they was exported to Poland (Warsaw) and Soviet Union (Rostov on Don).

Principal of trams´ work is equal as on Righoffer tram, but concept was differently manufactured. Driver had his own corner with chair and this tram had pedal driving (which was typical for trams for next 30 years). This was much more comfortable than in Ringhoffer tram where driver had to stand on his legs for all the driving time. For drive and braking were two different pedals.

After driver pushed the drive pedal, current was driven from wire through pilotmotor directly on resistors. There was a different type of resistor box in this type of tramway. Ringhoffer´s drive regulation was based on resistor boxes which was turned off by contractors. In T1 tram was rheostat manufactured as big cylinder with 77 steps called „*accelerator*“. Each step of accelerator had different value of resistance and there was dependence in how deep driver pushed the pedal, the higher step was contracted by rotating contact called „*eight*“ in accelerator and tramway went faster. During acceleration from zero speed is firstly contracted stable value resistors but in few seconds they are over-bridged and accelerator is contracted.

Braking of T1 tramway was pretty same except one change. Accelerator is contracted from the beginning of brake process and when rotating contact reach few last steps of accelerator, the mechanical brake is activated. It´s because breaking force of EDB is falling down very quickly in small speed and without it there would be no possibility to brake until zero speed. In comparison to Ringhoffer trams T1 tram had new type of brake and it´s magnetic-rail brake. It´s emergency brake.

For current collecting from the wires there was current collector which was one trolley pole. The second pole is rail. However, trolley poles were changed for two-arm pantographs in short time. With pantograph there is no necessity to have wire crossroads, so it´s cheaper technology for infrastructure and easier for service. Second reconstruction was changing motor-generator (MG) position from tramway floor higher, because there were some problems during winter with snow coming inside MG.

Operation end of these trams was different city by city. In Czech Republic ended operation the last T1 type tram in Pilsen in year 1987. In Prague most of them were later reconstructed to T3 type and next to T3R.P type which are still in service, but all interior and main regulation parts were changed for newer ones and have no any connection with T1 type.

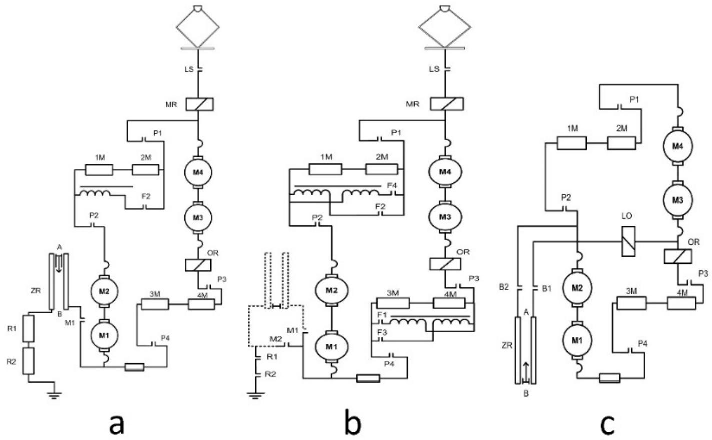
Picture 4 - Tram T1- repaired second prototype in Prague (photo author: David Cenek, 24.5.2008)

2.3. Tatra T3

Is four axle, double boogie one-way tramway from factory Tatra CKD. Prototype was built in 1960 in Smichov factory and was tested in years 1960-1961 on Prague rails (Picture 5) without passengers and year next was tested with passengers also the second prototype. By this year started most famous part of history of Smichov factory Tatra. Between years 1962-late 80´s were sold world-wide more than 14 000 pieces in 48 countries of the world, which is total world record in sold pieces of one tram type from one factory.

Tram T3 was built as an exchange for older type T2, which was not so successful because of big weight and it wasn´t energetic efficient at all. Differences between these two types were in design, in drastic loose of weight (in case of T3), changed accelerator and resistor regulation TR37 (see: Picture 6) and changed interior. In comparison to T1 is T3 slower and regulation, especially accelerator have instead of 77 steps, 99. Breaking features was pretty same as on T1, with three types of brakes (EDB, mechanical and electromagnetic-rail brake). DC motors are serially connected in one boogie typed TE 022 with total power 160kW. In comparison to Ringhoffer´s tram could 30 years of development increase power of trams more than 6 times. Some of these trams are still in service after reconstructions with thyristors or IGBT regulation in Prague as T3R.P. But mostly they are sold to Ukraine or North Korea.

Picture 5 - Tram T3 in year 1960 during test rides (photo author: Libor Hincica)



Picture 6 - T3 Tram schemes for a) acceleration, b) idle run, c) braking mode

2.4. CKD KT8D5 and KT8D5R.N2P

This tramway car was firstly tested in Prague streets in 1985. It meant a small revolution in Prague public transport, because this tram was totally unique with door on both sides and with two drives´ cabins. There was no other tramway in Prague which was tested with so much patience and preciseness on Prague tram-tracks. It´s cause by fact, that front and end part of this vehicle have boogies in bigger distance from cabin and that´s why front and end page have specific behaviour in curves. These two parts are in longer distance from rail axis during curve passing. Especially this ability could cause head-on collision with other tram going the opposite direction on the left rail or destroy a passenger zone. After these ascertainment were tenths of critical track places rebuild and from that times could this type from tram go to any part of Prague tram-network. In year 1986 there were 4 pieces from testing series of KT8D5 put in service in Prague. There was expectation of purchase 200 pieces, but finally there was in service only 48 pieces. Prague transport services had received these trams in 3 series, first were 4 pieces (9001-9004) as it is mentioned above, then second series (9005-9028) and third series (9029-9048) up to year 1995. Last two series differed from the first one by changed details on roof such as covers for brake resistors or covers for heating features.

Vehicle KT8D5 was 3-part double-direction tramway with thyristor regulation TV3 made by CKD Elektrotechnika. Both front parts was signed as A and B and middle-part was signed C, all coupled with toggle which is on the middle of boogie. Toggle part was covered with tent reminiscent to accordion.

Because of the that fact, this tram is not low-floor in 90´s acquired DPP few tramways of type RT6N1, but this type was total catastrophe while after 10 years they were still not able to service tram lines without damages and failures. That is the main reason why board of DPP managed to modernise KT8D5 traction systems and to rebuild middle-part (C part) to low-floor mode in year 2004.

Project of modernisation was realised with accompany of Cegelec (distributor of traction system and electronical parts of tramway), Pars Nova (total modernisation of A and B parts of tramway) and CKD Pragoimex (with project, design and build of brand new low-floor middle-C-part of KT8D5). Traction systems are totally changed. Old type of traction system TV3 is changed for direct-current traction system TV Progress , developed by company Cegelec. All traction systems are hidden under higher floor in both front parts. Current collector KE 23 was changed for semi-pantograph type Stemmann Fb 500, which are successfully used on single tram types T6A5.

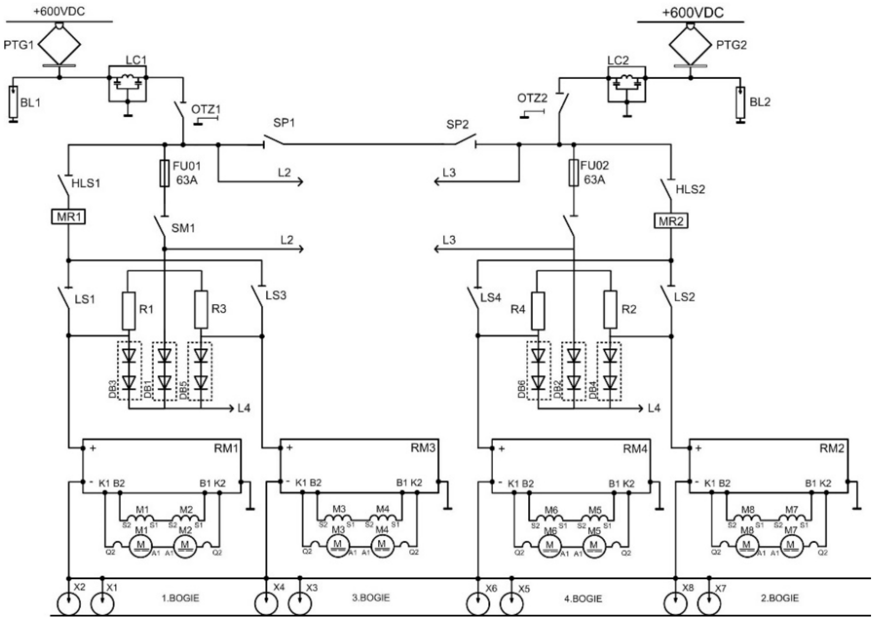
During this reconstruction was also changed design to complete not only visual effect but also better technical parameters (see: Picture 7). Near coupling system and on boogies was added additional iron covering with special anti-noise paint for minimization of acoustic noise.

Cabin is designed for driver´s comfort and unification with T6A5 type in driving features. Driving pedals are changed for hand-controller and buttons are designed on same positions as on T6A5 tramway. Vehicle also acquired camera system for checking of situation inside and outside of tram and real data are showed on 2 LCD displays which are set above front window with diagnostics panel.

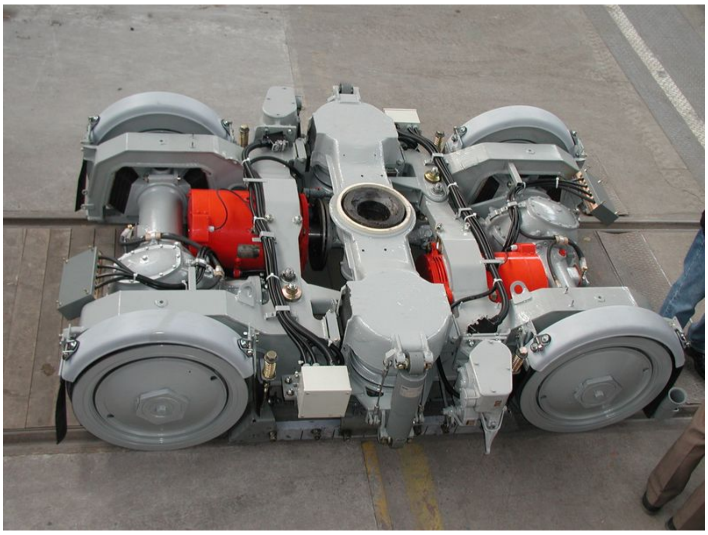
First these trams were reconstructed and modernised in year 2005 and renamed for KT8D5R.N2P type – which means KT8D5 Reconstructed- Low floor type with double-direction service and traction system TV Progress (see: Picture 8). In fact except of boogies was reconstructed all parts of this tram.(see: Picture 9)However, all the Prague KT8D5 have been already reconstructed, DPP bought 2 pieces of KT8D5 from Strausberg, Germany and 2 pieces from Miskolc, Hungary for reconstruction to KT8D5R.N2P type as well to have 50 pieces of these tram. (48 acquired – 1 destroyed in collision – 1 as historical vehicle + 4 acquired from Germany and Hungary).

These tramways are used for mostly passenger used tram lines, where is need of bigger capacity of vehicle or during track reconstruction works, especially after purchase of Californien rail-switch is used they ability of double-direction service.

Picture 7 - Tramway KT8D5R.N2P in Prague, Lazarska st. (author: Hans van den Sluis, 07.09.2012)



Picture 8 - Traction system TV Progress in KT8D5R.N2P, author: Daniel Sihlovec



Picture 9 - Boogie Comfort for KT8D5R.N2P with DC motors - red painted (Source: Krnovske opravovny a strojirny)

2.5. Skoda Transportation 14T and 15T

2.5.1. Skoda 14T

In the beginning of 21.century Prague was the only city which had no low-floor trams in common service. It was caused by problems of RT6N1 trams, which were in few years out of service and exported to another cities. Prague´s next try for brand new low-floor trams was set up in 2004 with selection procedure which won Skoda Transportation with their project of tram 14T for Prague. Conception of this tram came from 05T Vectra and 03T Anitra. Tram´s out design was developed in Porsche Design studios and interior was designed by artist Frantisek Pelikan.

Tramway 14T is 5-part low-floor one-directional vehicle (see: Picture 10) with length 30,25m projected for 69 sitting passengers. In total is possible to drive by with 279 passengers. Mechanical parts are projected on three double-axle boogies which holds parts No. 1, 3 and 5. Parts No.2 and part No.4 are carried with hinge bearings and coupled to parts with boogies. For easier drive though curves and hills this tram miss roof coupling between 3rd and 4th part. This tram is not 100% low-floored because there are two different heights of floor. One is in parts where boogies are and it is 600mm above rails and on carried parts there is 350mm above rails heads, which is much more comfortable to get in for disabled or older people, mothers with prams, or for bicycles.

There are boogies which are projected as two-axle with two asynchronous traction motors with total power 90 kW on the Picture 11. Every boogie is counted as one motor-group which has its own traction converter with use of semi-conductor IGBT components. Total power of all converters is up to 1100kW in drive regime and 2000kW in brake regime.

Vehicle consist brake system as well. There are 3 types of brakes- electrodynamic, electromagnetic and mechanic brake. Electrodynamic brake can recuperate energy back to supply network, although it can also burn this energy in brake resistors, if the supply network isn´t able to receive energy back. This can happen if in the particular part between two isolated passages, there is no other tram in this part who can spend energy made by tram. Electromagnetic brake is used as emergency brake and it is known from older types of trams. Mechanic brake is constructed as disc-brake.

Tram´s control system is designed for self-check location, angle and vehicle´s speed and in comparison to chosen driving regime is able to edit parameters given by driver with hand-controller. It consists sensors for angles between parts and according to calculations tram can automatically edit parameters of drive such as maximum speed in curve, which is signalised on display in front of driver.

Most of power components are located on the roof in boxes, which is caused with low-floor type of vehicle. Front part of tram consists semi-pantograph current collector Lekov, disconnector and contractor box. Traction converters are situated on 2^{nd}, 4^{th} and 5^{th} with brake resistors. Static charger and batteries is situated on the 2^{nd} part of tram and other free space on 5^{th} part of tram is used for ancillary drives. Non power electronics and control electronics are hidden in drivers cab.

In current situation these trams are out of service in depot except of 4 pieces which are in service. This is caused with many main-frame failures, because many failures were caused by wrong design of mechanical parts, which is not appropriate for Prague tram network.

Picture 10 - Tram Skoda 14T is crossing Sokolovska street in Prague (Photo: butzi.cz, G.A.S.)

Picture 11 - 14T boogie with primary and secondary springing (Photo: Prazsketramvaje.cz)

2.5.2. Skoda 15T

After new millennium start and final retail of RT6N1 and purchase 14T type, DPP still managed question of low-floor tramways. There were many information from 14T service about failure project parts and DPP realised to buy other type of low-floor tram. Skoda transportation was interested in this task and developed a brand new type of 100% low-floor tram especially for Prague streets with usage of all new technologies and finally this 31.40 m long tram was entertained to DPP management and public on 10.4.2008. Actually there are about 150 pieces of these trams in Prague. Total contract is for 250 until the year 2018. First 125 pieces were in version 15T. Now DPP receiving edited version 15T4 with air-condition, Wi-Fi system and new design with less body parts for easier repairs after collisions.

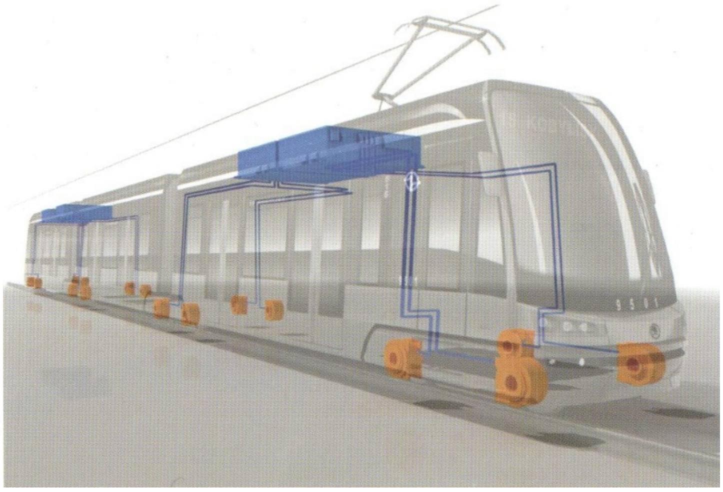
Main difference of this tram is, that it is designed and projected on base of years of experiences with tram service in Prague and main tram parts are designed for optimal service also in critical parts of Prague tram network. Boogies in front and back parts are designed in most front and most back place in construction abilities to minimize digression of these parts and potential collision with other traffic means. In addition to this design hack, are boogies possible to rotate around axis in bigger angle scale, which was not possible on 14T. Vehicle consist 4 parts coupled together with hinge bearings on extremely-low settled boogies.

Boogies are manufactured partly as steal casted parts into frames and partly as welded. As we can see on Picture 13 wheels are not coupled into axles as we used to know, but they are stack on ball bearings. Wheel, in this case no axle, is put into moving not by engine which is coupled on axle with gear box, but on this tram, engines are constructed directly on wheel to transfer mechanical torque directly on wheel, which we can see on Picture 12. This eliminates losses on wheels and rails and noises when tram is going through curves, because wheels on left side do another trajectory as wheels on right side of tramway. To put on move this tram is task for 16 synchronous motors with permanent magnets which is really unique concept of tramway drive. Every this motor have 45kW power and exactly because of use motor for every wheel, it is possible to go with tram on standby drive even only with one boogie working.

Power electronics, as well as traction converters, are hidden in boxes on roof part of tram (Picture 14). For current collecting is used semi-pantograph current collector settled on the roof of first tramway´s part. Control system is hidden in driver’s cabin, with breaker box as well. System is designed for adaptation for GPS map of Prague tram network and location of tram crossings, curves or places with regulated speed. It means, that system can edit command from driver via hand-controller if calculation of system is more appropriate for pass the curve or crossing.

Picture 12 - Detail of connection between wheel and motors (Source: Prazsketramvaje.cz)

Picture 13 - Boogie of 15T without motors, springing and other features (Source: Prazsketramvaje.cz)



Picture 14 - Traction converters of 15T located on roof of front and back parts (Source: Company Materials Skoda Transportation)

3. Alternative power sources in city transport

3.1. Energy flows and loses in tramway service

There are three different possibilities about use of energy in tramway produced by electro-dynamical process of braking. We can spend this energy in braking system (BS) and change it for heat, for which we have to project additional cooling system, share this energy back to the supply-network. However this method is possible only when there is another vehicle in supplied isolated part which could use this energy for its own move. Third possibility is to spare this energy right in vehicle in batteries and supercapacitors.

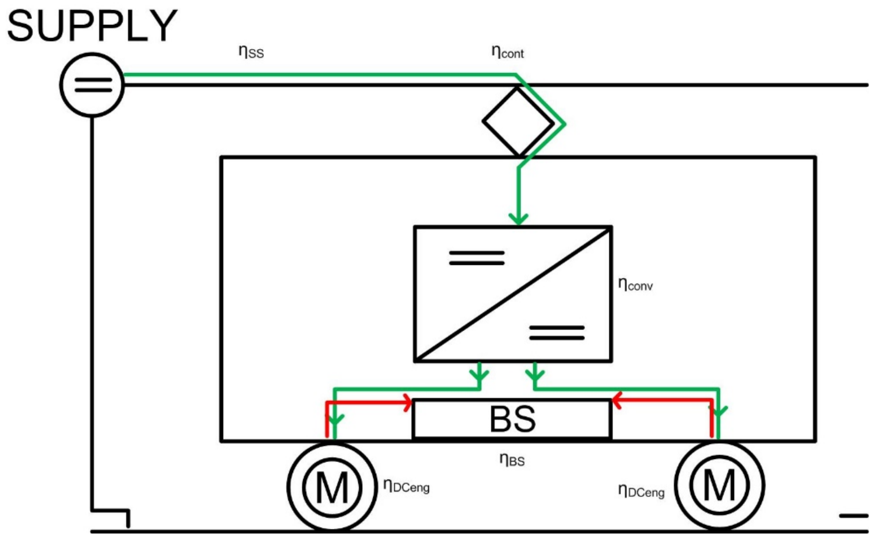
3.1.1.Energy flows and loses in tram with no recuperation or batteries system

First loses in feeding line (**green line**) are set in supply network in dependence on distance from supply point (η_{SS}) and contact of current collector (η_{cont}).This device is mostly manufactured from aluminium and mass have a weight about 100-200kg (depends on model). This system is staying in connection with wire because of mechanism, which pushes on spring by pressured air current collector next to the wire and all loses depends on if pressure value is right to stick collector shoes to the wire.

Loses in converter are higher than in other types, because it´s obvious that in this types of trams as a “converter” (η_{conv}) is used resistor or set of resistors, which could be set to the circle as accelerator on T3 tram used in Prague. This device shifts resistors from that one with highest value until that one with smallest value. The lowest value of resistance, ergo lowest loses in converter are when pedal is pushed to the floor.

Some loses of energy are in DC engines (M - (η_{DCeng})). It´s because, especially in this work we use only DC engines and it have no contactless energy transport between rotor and input of motor. We use carbon contacts as input for rotor current to excite rotor magnetic field. All these loses are in first way of use of energy, it means when tram is accelerating.

However biggest loses we have during brake process (**red line**), when all the energy produced from moving into electric energy in DC engine is burnt in braking system(η_{BS}), which is resistor. It means that all this energy we just transform in heat, which we have to carry away.



Picture 15 - Energy flow - Scheme of tramway with resistor braking systems (Author: Daniel Sihlovec)

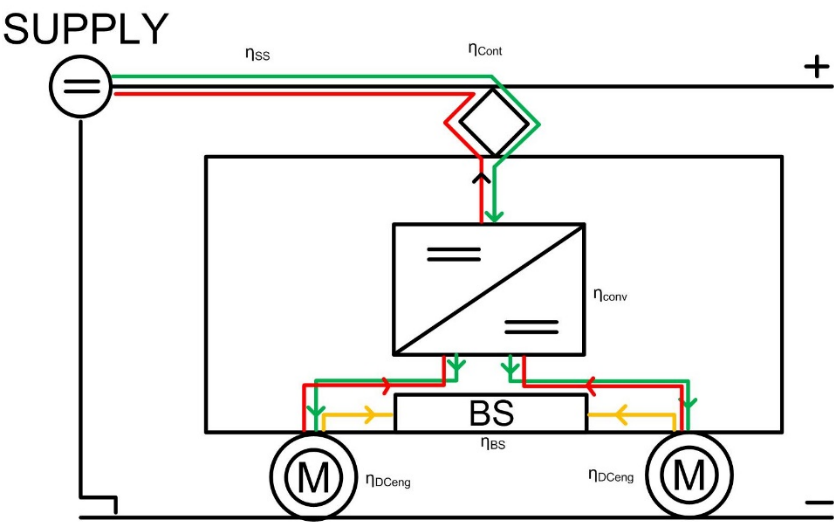
3.1.2.Energy flows and loses in tramway with recuperation

In this type of tramway are input loses the same as in tramway above. Loses of supply system depends on distance from supply point (η_{SS}) and contact of current collector (η_{cont}). In this type is different that, we can calculate these loses twice, because when we distribute energy (**green line**), we did during electrodynamic braking we distribute that the same way (**red line**) like the energy flowed to vehicle.

Loses on current collectors in way of pressure of collector shoes and good contact is eliminated because these tramways mostly have newer types of current collectors which are easier to operate. Loses in converter (η_{conv}) are mostly eliminated as minimal. It´s given by the fact, that if the tram can recuperate it have to have semi-conductor converters, which are manufactured from new types of semi-conductors and loses of convertor as closed system is about 3-5%.

Some loses of energy are in DC engines (M - (η_{DCeng})). Loses in engines are eliminated to minimum as well, which is caused with fact, that these vehicles mostly have newer types of engines such as asynchronous or synchronous. We don´t use carbon contacts as input for rotor current to excite rotor magnetic field.

All these loses are in first way of use of energy, it means when tram is accelerating. Loses during braking process we can interpret as losses in convertor in energy back-flow to the supply system, because almost all energy made in engines flow into convertor and back to supply system. That is why we can eliminate loses in braking system (η_{BS}) during braking process, but when there is no other vehicle in supplied isolated part of supply system, which can spend this energy, all energy made with engine during electrodynamic braking is burnt in braking system (**yellow line**) which causes additional loses (η_{BS}).



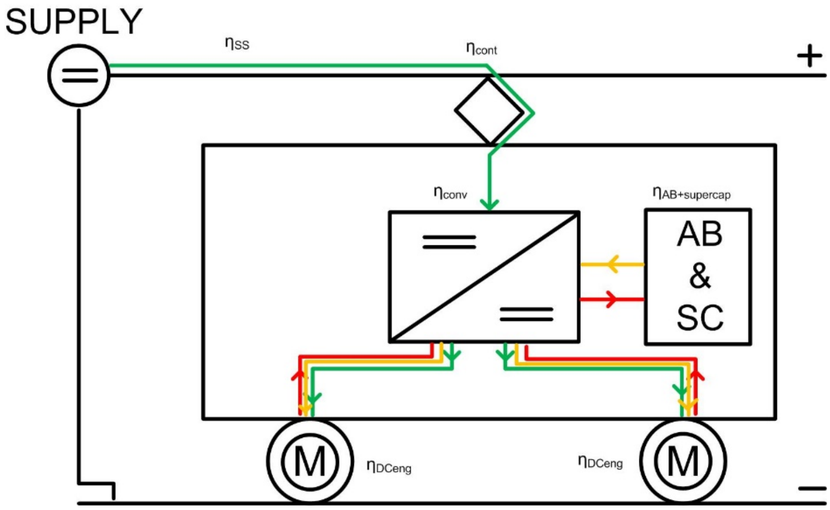
Picture 16 - Energy flow - Scheme of tramway with allowed recuperation (Author: Daniel Sihlovec)

3.1.3.Energy flows and loses in tramway using batteries and supercapacitors

Input loses are same in all types of tramway. First loses we have in supply system and contact between supply system and tramway, current collector. These loses are η_{SS} as loss in supply system and η_{cont} as loss in current collector. When we follow feeding line (**green line**) we have next loses in converter η_{conv}, which are practically minimal and we can forgive them. This is caused by using technology of semi-conductor converters.

In this type of trams, for example like tramways type 15T in Prague, where can be installed these devices or 27T, which service Chineese city Qingdau and from Skoda Transportation use synchronous engines(M - (η_{DCeng})). with permanent magnets. These types of motors have really low loses, which, especially synchronous motors with NdFeB permanent magnets, are about 2% more efficient than best asynchronous motors.

In braking mode (**red line**) we have some losses in engines, some of them are in converter and some losses are in supercapacitors and accumulators ($\eta_{AB+supercap}$), which is based mostly with fact, that we can´t discharge 100% energy from them. Some losses are as well during opposite process when we feed converters and engines from AB or SC (**yellow line**). We can eliminate braking loses (η_{BS}) because of use of supercap and AB where is all energy saved.



Picture 17 - Energy flow - Scheme of tramway with accumulators and supercapacitors (Author: Daniel Sihlovec)

3.2. Reasons for use of APS in city transport

Modern trend in corporate and personal life is to decrease consumptions of electric energy. This is valid in public transport as well. In many European public transport companies, in fact all around the world, it´s more common to use recuperation mode of electric transport vehicles. Principle is really simple. It is use of mechanical energy which have mass of vehicle in move and this mechanical energy is transformed continuously back into electric energy through engine, which now works like generator and produce energy which is given back to network. There is only one problem which makes this effective in 100% cases and it´s a condition, that in the district between two supply points have to be other device, or better we can say another electrical vehicle, which is able to use this recuperated energy. Otherwise, we have to burn this produced energy in resistor and in fact it is destroyed in braking resistor as transformation on heat.

Other possibility, which have started to be more popular few years ago, is to project to vehicle energy accumulators and change direction of energy flow from braking resistor or network to energy accumulator and save energy in there. This energy have many possibilities for use. We can use it in tramways, trolleybuses or electro-buses. Main reason of purchasing vehicle with accumulator is to use this vehicles in parts of the city where no wires above to supply all vehicle energy demands are. Accumulators in these kinds of vehicles are charged during time when vehicle in connected to the network and then use this energy for drive in parts of city, where there are no wires. Secondly, we can use saved energy for supply peak demands of energy during acceleration from stops or crossroads, when demand of energy is higher than during uniform motion. These devices can be installed for supply ancillary drives, for lighting supply or supply all electronics in vehicle. Although is this technology still really expensive, costs used for purchase of vehicles with accumulators could be lower than costs of construction and service of new tramway or trolleybus wire network, but of course these cost depends on surface of ground, weather conditions or other effects.

3.3. Types of energy storage devices

For this thesis is not necessary to name all types of energy accumulators, for example such as flywheel, which is unappropriated for topic of this work, but it will be mentioned as general knowledge. Especially for topic of city railway transport, for us are suitable two of them and these are accumulators based on electrostatic field and accumulators based on electro-chemical exchange.

3.3.1.Flywheel

Basic device for storage energy is a flywheel. This machine is a rotating disc spinning around its axis. Basic principle is to storage mechanical energy from kinetic energy of wheels. It works, when the flywheel´s rotor is accelerated to high speed and maintain the energy in the system as rotational energy. Flywheels can be used to produce high power peaks.

Between their strength sides belongs efficiency, long life time or high energy density. It is cause by fact, that rotor is made in a sealed vacuum enclosure and use magnetic suspension for reduce friction. In addition to fact, that this is a mechanical device, they do not suffer from temperature changes or memory effect. On the other hand a low specific energy is as a main problem of this device. If we can compare this technology with batteries, it is much more expensive in applications in time longer than 10 minutes range, due to cost of flywheel and difficult manufacture conditions. To main threats belong danger of explosion, in case of exceed of tensile strength. It´s really difficult to use flywheels in a larger scale that is why it is not suitable for this case study.

3.3.2.Accumulation based on electro-chemical exchange

3.3.2.1. Fuel cells

Main principle of accumulation in fuel cells is to combine hydrogen and oxygen electrochemically to produce electricity. By-products made with this technology are only water and heat. Fuel and oxygen are continually but separately brought to electrodes and reaction products are taken separately away.[12] Fuel can be hydrogen, ammonia, formaldehyde or earth gas. Main equation of chemical reaction we can write in this easy formula:

$$H_2O+0_2/catalyst=>H_20 + Heat$$ [3]

3.3.2.2. Lead-acid accumulators

It is one of the most used electrochemical energy storage. Electrolyte is water reduced sulphur acid, which is divided on sulphate ions with negative charge and hydrogen ions with positive charge. Active surface of anode is lead, active surface of cathode is lead dioxide. During discharging are electrons excited from anode, which go to cathode. During this time is lead dioxide reduced on water and lead disulphate. There is continual proportion between rise of temperature and capacity, but also losses and accumulator life is shorted under higher temperature.[4]

3.3.2.3. NiCd

Higher level of accumulator evolution is nickel- cadmium accumulators which have longer life, ability of quick charge, they are immune against overcharge and what is more important in vehicles which work outside is that, they have smaller capacity downgrade in lower temperatures. Life-time of battery is affected by intensity of drive just on accumulator, value of charging voltage or in-service temperature. Auto-discharging is higher during first 14 days after charge and just after fully charged accumulator, which makes this accumulator not so suitable for use in transport vehicles, where is assumption, that charge and discharge process will be used more often. [4]

3.3.2.4. NiMH

After years of experience with NiCd accumulators was cadmium changed for metal hydride composition which bonds hydride. Metal hydride have huge capacity for hydrogen, which is not based under pressure and endurance against oxidation. Nickel is used for cathode, metal hydride composition for anode, around electrodes is electrolyte and separator. Use of Ni and MH allow use this accumulators under low temperatures. However, in bigger temperatures is efficiency downgrades very quickly. [4]

3.3.2.5. High power Lithium-ion batteries based on cobalt

Most lithium-ion batteries for portable applications are cobalt-based. The system consists of a cobalt oxide positive electrode (cathode) and a graphite carbon in the negative electrode (anode). As another types is it possible to use $LiNiMnCoO_2$ (NMC) or $Li_4Ti_5O_{12}$ (LTO) for cathode. Ability of good lithium ions acceptance and sharing is demanded from matric.[5,6] Charging characteristics of Li-ion accumulator types are really close to NiMH accumulators.

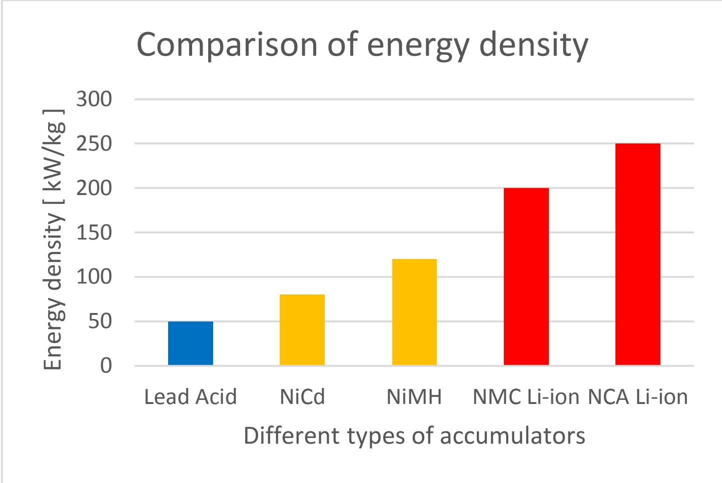
One of the main advantages of the cobalt-based battery is its high energy density. On the graph 1 we can see compare of energy density (Wh/kg) of Lithium-ion accumulators made with different cathode material in comparison to lead acid accumulators, nickel-cadmium or nickel-metal-hydride accumulators. Main improvement is use of cobalt with mixture of Aluminium, Manganic oxide, Cobalt or for example Titanium, which upgraded energy density, but has disadvantages as missing possibility of allowance of high load currents and it is not so thermally stable.

Although of some disadvantages is this type of batteries used also in transport systems, for example in cars- Tesla Model S (60 kWh or 85kWh) or another product of Tesla company, Powerwall batteries, with their 6,4kWh model which proves that this technology still didn´t reached its maturity and is still in progress. However, the accumulators with biggest capacity like to Tesla model S which contains 7 104 battery-cells in 16 modules, costs about 10 000 – 30 000$ which is about 20% of car price, is there an expectation of mass-produce in the future and price downgrade.

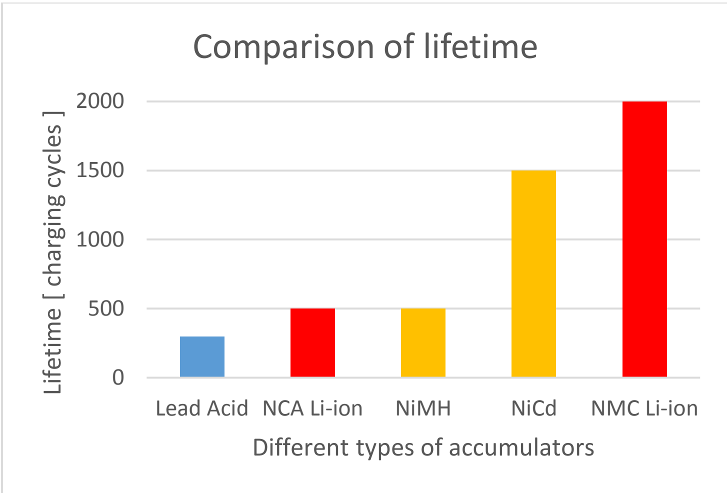
3.3.3. Comparison of different types of electro-chemical accumulators

All of these types of accumulators based on electro-chemical exchange have different properties. Suitability of each electro-chemical accumulator for use in transportation depends on many factors such as volume density of energy [Wh/kg], Life-time [Number of cycles] or Loses via auto-discharging. In addition to these could be also specific output [W/kg] or power efficiency [%].

Some of these accumulators have characteristics which are not suitable for use in devices which are in use for a long time during a day and the device have demand for example for quick use of all accumulated energy, or this accumulator have to stand many charging cycles in a day. There are 5 main factors we need to consider in situation of designing or projecting a vehicle with drive based on energy accumulators or with energy accumulators as alternative power source, which is addition to power supply from wire network and it doesn´t matters what kind of accumulator it is.



Graph 1 - Energy density of NCA and NMC lithium-ion accumulators in comparison to NiCd, NiMH or Lead acid accumulators (Source: Battery university)



Graph 2 - Comparison of accumulator lifetime between different types of accumulators (Source: Battery university)

In the graph above we can see comparison of energy density and accumulator lifetime between few types of electrochemical accumulators. Li-ion, which are most powerful of them, are used in transportation, especially in electro-cars (EV). Although many of them have no ideal characteristics, they are used for devices where is no necessity to charge so many times. For example vehicle Tesla model S, is projected as vehicle which is charged about 40-50 times in a year, which means discharging process during use takes about 7 days. By using this rule is assumption to use vehicle accumulator for 15 years. In numbers, one change of batteries cost about 44 000$ and only calculation into 15 years of cheap driving is this technology still really expensive. In summary, if we see how much energy is it possible to save and how long life of this electro-chemical accumulator is this technology not appropriate for city transport especially in tramways, where we would like to use spared energy as feeder of peak values during acceleration and charge this device with energy from EDB. For this purpose is more appropriate to use accumulators based on electrostatic field, which can save energy not as chemical substance, but as charge.

3.3.4. Accumulation based on electrostatic field

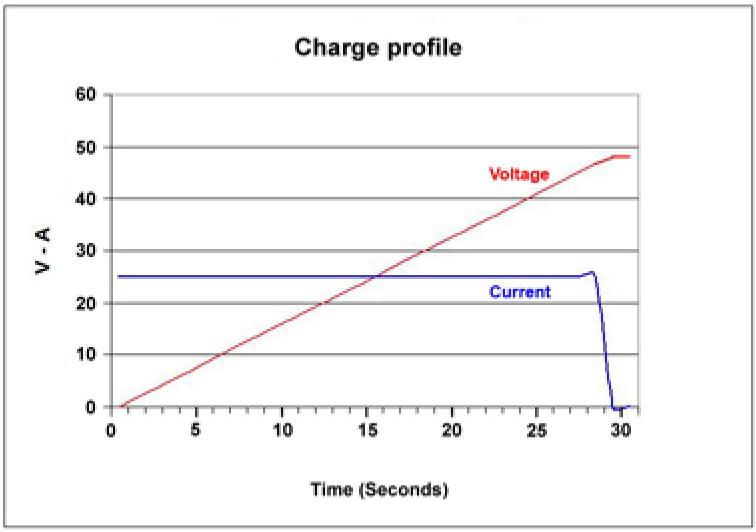
In comparison to electro-chemical energy supplies, electrostatic are appropriate more for applications where is needed quick charge, quick discharge and frequent charging cycles during short period of time with high-rated current. Main function attributes are to apply voltage differential on positive and negative plates, which charges the capacitor. There are three most basic capacitors:

a) Electrostatic capacitor with a dry separator
b) Electrolytic capacitor
c) Supercapacitor

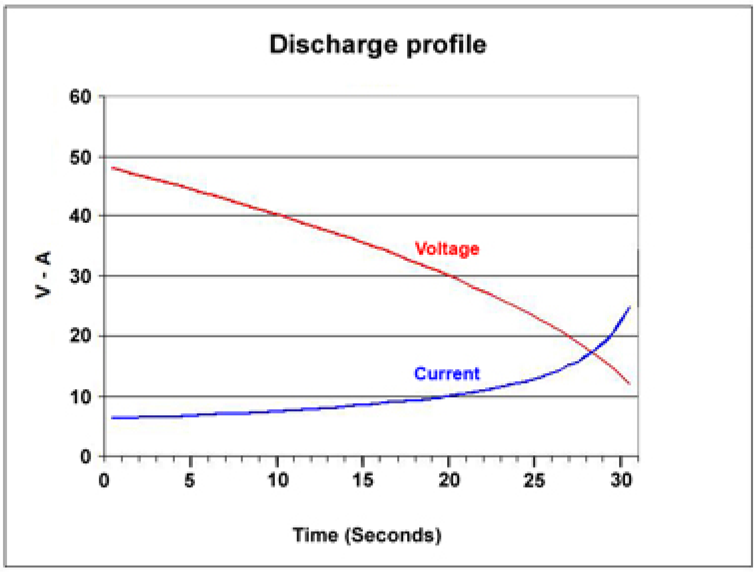
First category capacitors have really low capacitance (pF or μF) and they are mainly used in low-voltage electronics, especially in radio communications and higher frequency electronics. Electrolytic capacitor provides about 1000-times higher capacity than dry-separator´s capacitor, but for use in power electronics is this value still not acceptable. Supercapacitors, or ultracapacitors (double-layer capacitors) are different from classic capacitors in way, that they have capacity not in pF or μF, but mostly in Farads. First tries of supercapacitor technology was noticed in late 50´s, but for this technology there was no appropriate commercial applications. This technology of energy storage was re-discovered again in 90´s with improved technology performance and better materials with lower cost. Most technology of supercapacitors was evolved from battery technology, although it was used special electrodes and electrolytes. Especially Asymmetric Electrochemical Double Layer Capacitors (AESLC) uses battery like electrode to gain higher energy density, but with shorter life cycle in advance. Then was tried graphene electrodes in which was belief to improve quality and energy density of supercapacitors and batteries. After 15 years of development technology step back to Electrochemical double-layer capacitor (EDLC) with carbon-based burdens and organic manufacture. This technology is easy and cheaper to manufacture.

All capacitors have voltage limits. Electrostatic capacitor can be made in high-voltage regime, supercapacitor is for lower voltages as 2.5-2.7V. With actual supercapacitor´ s technology is also possible to have higher voltage than 2.8V, but this ability reduces service life of this capacitor. Only possibility how to get higher voltages from supercapacitors is to use a serial connection of them, but it is strongly recommended to use a voltage balancing circuit in use of more than three capacitors connected in series. [7]

This is recommended to use like a prevention against overvoltage of any of supercapacitors connected into circuit. Although use of more pieces decrease total capacity of this “battery” and increase resistance this is the most appropriate way how to receive higher voltage. Supercapacitor have mostly charging time about 1-10 seconds. Charge and discharge characteristics as it is on Graph 3 and Graph 4 below, we can describe as in case of electro-chemical accumulator with voltage which is increasing linearly during flow of constant charging current, when capacitor is fully charged, the current drops down to zero. During discharging process voltage decrease linearly on discharge. As optional solution we can use DC-DC convertor, which maintains the level of power by drawing higher current with dropping voltage. Supercapacitor is not subject to overcharge, so in time when it is full of energy current simply stops flow. Provision must be made to limit the inrush current when charging an empty supercapacitor as it will suck up inside all it can.



Graph 3 - Supercapacitors V-A diagram - charge process. [7]



Graph 4 - Supercapacitor V-A diagram - discharge process [7]

Supercaps are ideal when a quick charge is needed to fill a short-term power need. They are most effective to bridge power gaps or fill a peak value instead of hard power-source for seconds or minutes. They are installed for example in

Long Island Rail Road (LIRR) in New York or in Japan. On LIRR is used for prevent voltage sag and reduce peak power usage, by using 2MW supercapacitor bank. This system must provide continuous power for 30 seconds and fully charge itself in the same time. Japan also use large supercapacitor banks with nominal value of power 4MW. They are installed in commercial buildings to reduce grid consumption at peak demand times and ease loading. Supercaps have low specific energy and are expensive for manufacturing, because they are not mass manufactured, so it means high cost per watt of energy.

3.4. Comparison of electrochemical accumulators and supercapacitors and their suitability for application as alternative power source of tram

Supercapacitor has specific energy between 1-30 Wh/kg, which is about 10-50 times less than Li-ion accumulator. To another disadvantages belongs discharge curve, where the electrochemical accumulator delivers a steady voltage and Voltage on SC decreases on a linear scale. This fact causes reducing spectrum of usable power.

We can image that on 6V power source, which is allowed to discharge to 4.5V, afterwards the equipment cuts off. If we can compare supercapacitor to electrochemical accumulator discharging characteristics which are flat, SC will be discharged within first quarter of the cycle and the remaining energy is for us unusable. However we can use a DC-DC converter to recover energy dwelling in the low voltage band. In case of electrochemical accumulator we can use 90-95% of energy.

If we compare in self-discharge abilities, supercapacitor have it higher than electrostatic capacitors and somewhat higher than electro-chemical accumulator. In case of supercapacitor we can say 50% of his energy by self-discharge in 30-

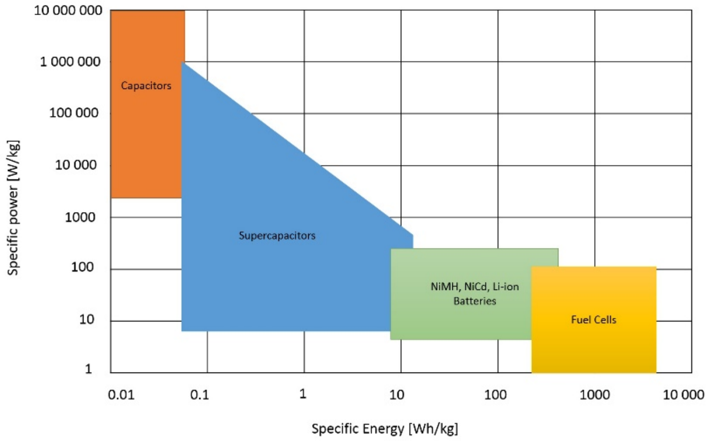
40 days, on the other side Lead acid or Li-ion batteries discharge itself about 5% per month.

Comparison of number of charge and discharge cycles and in general life-cycles is in summarization better for supercapacitor, which have charge and discharge cycles in virtual way unlimited and in 10 years in service his capacity downgrades to 80% of his full capacity.

Supercapacitors can be also used in powertrains, where the virtue of ultra-rapid charging process during regenerative braking (EDB) and delivery of high current on acceleration makes supercapacitor ideal as a peak-load enhancer for hybrid vehicles. One of the main goals for this is as well huge range of working temperatures in comparison to battery and long life in meaning of charging and discharging cycles. Between other advantages of supercapacitors belong as well high specific power with low resistance, which enables high load currents or simple charging without possibility of overcharge

Function	**Supercapacitor**	**Lithium - ion (general)**
Charge time	1-10 sec.	10-60 min
Cycle life	1 million/ 30.000h	500 and higher
Cell voltage	2.3 - 2.75 V	3.6V nominal
Specific energy [Wh/kg]	5 (typical)	120-240
Specific power [W/kg]	Up to 10.000	1000-3000
Cost per kWh	10.000 $ (typical)	250$ - 1000$ (large system)
Service life (industrial)	10-15 years	5-10 years
Charge temperature	-40°C to 65°C	0°C to 45°C
Discharge temperature	-40°C to 65°C	-20°C to 60°C

Table 1 - Comparison of main features of supercapacitor and Lithium - ion accumulator [15]



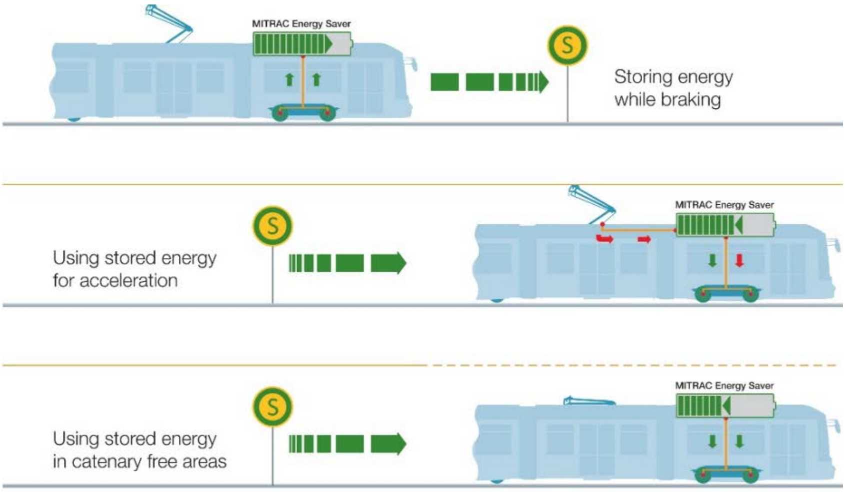
Graph 5 - Table of comparison of specific power and specific energy of accumulators mentioned above (author: Daniel Sihlovec)

To summarize all given information mentioned in both, Table 1 and Table 2 above, supercapacitors are ideal when a quick charge is needed to fill a short-term power need, whereas batteries are chosen to provide long-term energy. Combining these two into one hybrid system we could reach perfect conditions for service of alternative power source in city railway transport vehicles, in which batteries have reduced stress, when reflects in a longer service life.

3.5. Bombardier system MITRAC using supercapacitors as alternative power source in Mannheim, Germany

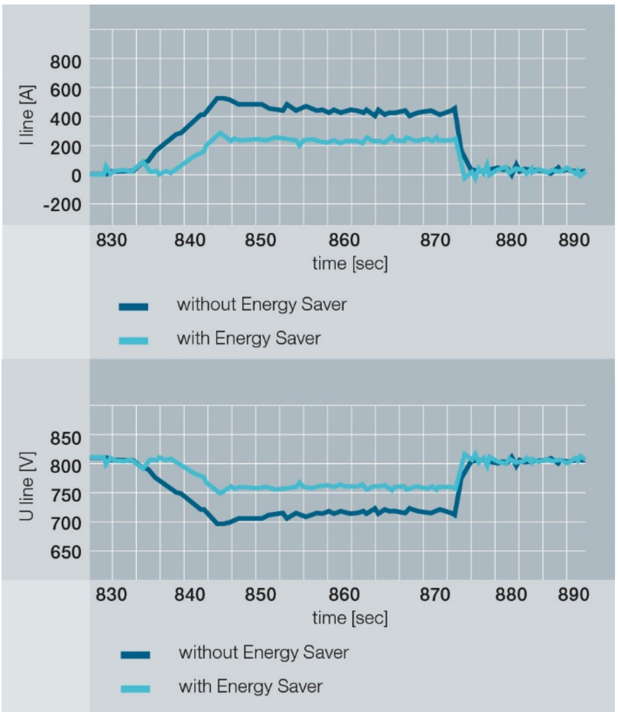
Although technology of supercapacitor use is relatively new, it has been already used in some places over the world. Our example is german city Mannheim, where people in city could firstly try this technology in 2009. Nowadays transport services of Mannheim (Rhein-Neckar-Verkehr GmbH) city owns thirty vehicles with addicted supercapacitors. This technology is primarily used for feed of voltage peaks and improve of recuperate braking abilities of vehicles. In current situation they are testing new generation of batteries PRIMOVE (lithium-ion on base mangane and cobalt, NMC) with MITRAC system (using of ultra-capacitors). Total record in case of battery trams was done exactly in

Mannheim and it was 41,6 km without any charge or supply another way (most of the tracks are built without supply-network).[8]



Picture 18 - Scheme of Bombardier MITRAC system (Source: Bombardier marketing prospects)

Complete system based on Bombardier MITRAC Energy Saver can reduce consumption or a light rail, trams or metro, up to 30% of traction energy, and about 20% of total costs. System is developed for downgrade peak currents and spare energy during electrodynamic braking. This system can be used as well as a performance booster, which enhances the performance of a vehicle by adding more power during acceleration of the vehicle. Measurements during acceleration up to 50 kph^{-1} showing us a peak power demand and voltage sags in supply-network while using system Bombardier MITRAC (light-blue line) and without using of it (Paris-blue line) as it is showed in Graph 6.



Graph 6 - Comparison of system information with or without MITRAC system: 1st graph - Acceleration currents demand, 2nd graph- difference in voltage sags (Source: Bombardier marketing prospects)

We can see on these graphs that this system really can spare energy and help to avoid voltage sags in supply network. On the first diagram is recorded in about 40-50 seconds of acceleration to speed 50 kmh^{-1}. Without using MITRAC system we can see that acceleration currents can rise in 10 seconds on value about 500A. If we consider that in Mannheim is used supply network value 750 VDC, by using formula for calculating DC power:

$$P = p(t) = U.I$$

is the value of DC power 375 kW. In comparison to first result with using MITRAC system downgrade acceleration currents to value about 250A, which equals to power of 187,5 kW, which is spare half of power from supply system. This causes lower voltage sag in supply network. In this case we have stable about 800VDC and without using system MITRAC fall down voltage to value 700VDC, but if we compare this situation with use of system MITRAC, we can obtain result 750VDC and according to graph we can see, that this supply system characteristic is more stable and have not so many oscillations as in case of tram with no MITRAC system.

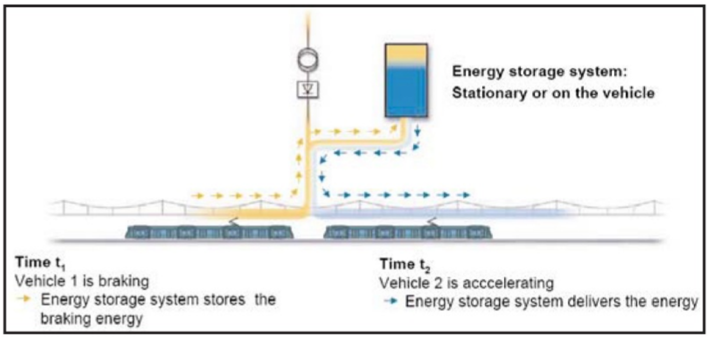
3.6. Siemens SITRAS stationary-system

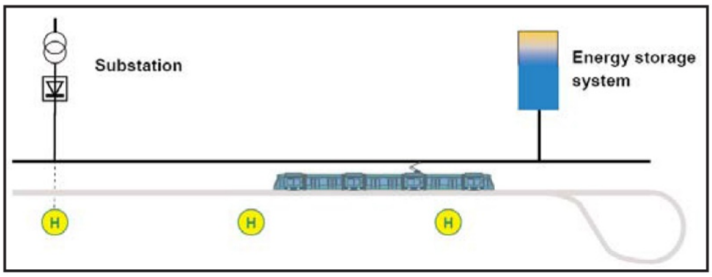
System SITRAS SES (Static Energy Storage) works on basic principle of supercapacitor bank (3000 Farads and 2.7V). These are installed at some points of the network to recover the energy of the vehicles operating on the line and voltage sags optimisation.

The system is built from supercapacitors interconnected and mounted in massive shelf located on substation supply level and connected parallel. We can find this system in full service many cities such as Bochum, Cologne, Dresden (Germany), Madrid (Spain) or Peking (China).

The system, used in Cologne works as energy saver. By this device company saves about 320.000 kWh annually as average value, but in fact maximum value, depending on circumstances could be up to 500.000 kWh in a year.

Another situation is in Madrid, where system is in use to stabilize voltage in metro. Main function is to stabilize voltage when few vehicles accelerate simultaneously. This means that current demand is bigger than obvious and voltage drops down. The system is then used to fulfil demand of more vehicles accelerating in one moment. By measurements it was significantly proved that voltage sags with SITRAS use are to value 530V, which before was only 490 V, based in 600V supply system. [11]





Picture 19- Picture above shows principle of SITRAS system, 2nd picture shows parallel connection in supply system (Source: Siemens marketing prospects)

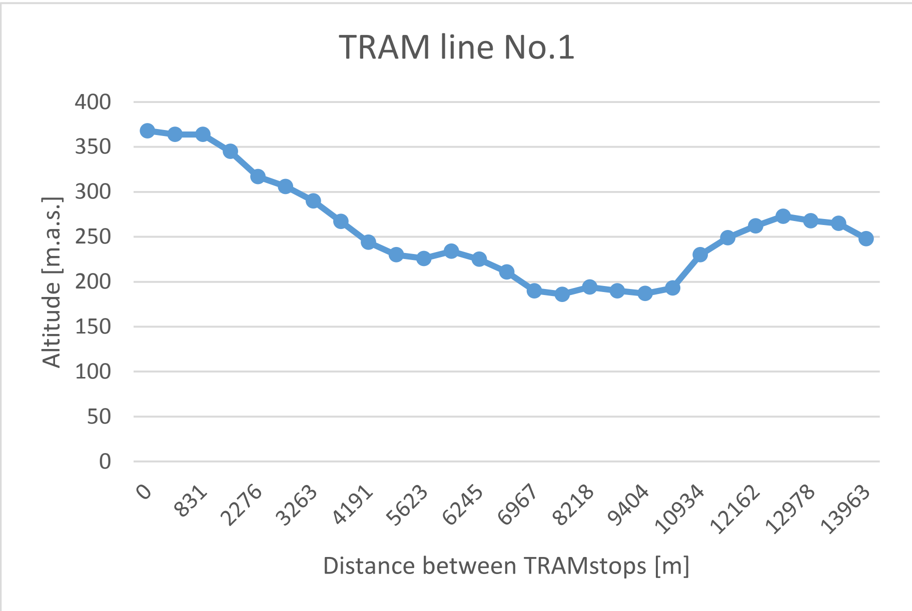
3.7. Siemens SIBAC on-board system

This system is quite similar to Bombardier MITRAC system described above. This system is as second manufactured system from Siemens, which will be offered. Main difference between SITRAS and SIBAC system is, that SIBAC system is container of interconnected supercapacitors, but these capacitors are on vehicle. With this system was expected savings about 20-35% which depends on circumstances, but this number is pretty close to results of Bombardier MITRAC system. The system is used in several German cities in Siemens´ Combino trams in Düsseldorf or Postdam.

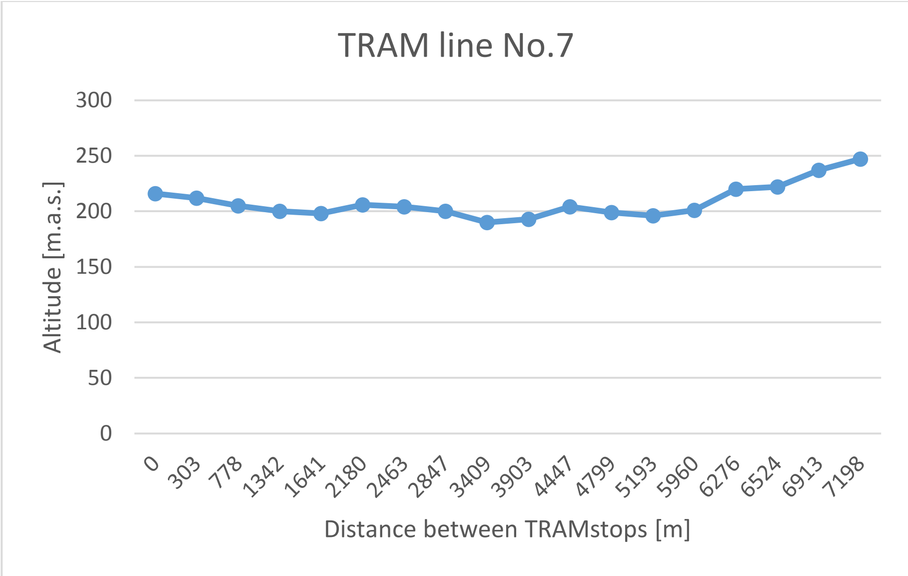
4. Real data and simulation

4.1. Chosen line for physical interpretation of tramway line in Simulink

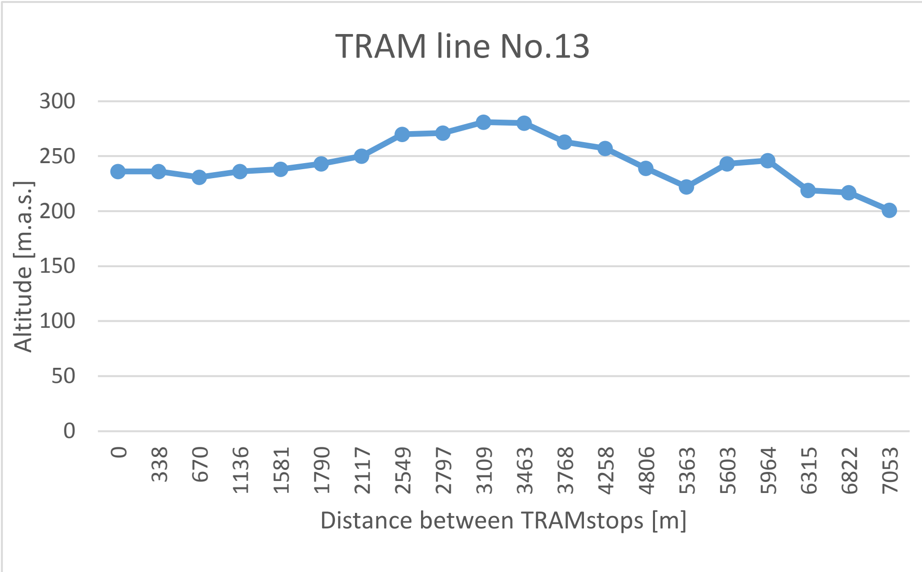
Main task of this work is to check in MATLAB simulation availability of use of supercapacitors in Prague tramway lines. As the first data we need to choose our line in dependence to altitude. City centre was built in valley but most other city parts are built in hills around Prague. To implement our data is best way to choose line which contains climbing into steep hill and downhill as well. I have chosen three different tram lines. It´ s Tram line No.1, Tram line No.7 and Tram line No.13. Main task was to compare track abilities and find the most suitable line track for not only rare use of supercapacitor energy. I set all the data into graph to have visual output and as most suitable was chosen TRAM line No.1 which we can see on Graph.7. To compare our visual output results from tram lines No.7 and No.13 we can see it on Graph No. 8 and Graph No.9.



Graph 7 - Alltitude profile of Tram line No.1



Graph 8 - Alltitude profile of Tram line No.7



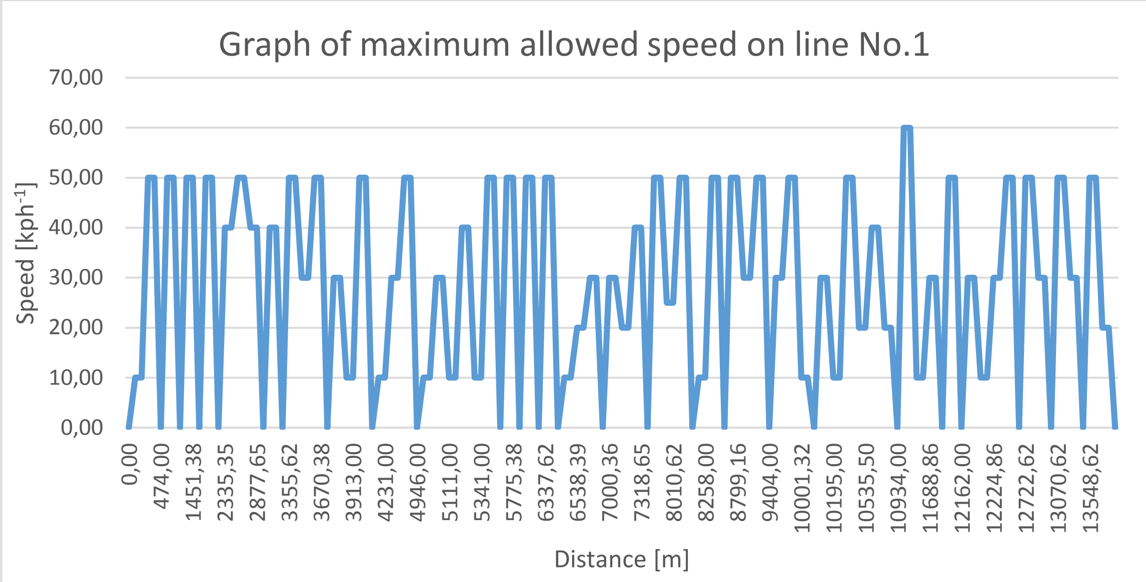
Graph 9 - Altitude profile of Tram line No.13

This tram line No.1, which we will interpret in our case study, is in service through Prague 6, 7, 8 and 3 and it rides from western part of Prague to the eastern. This line have 27 stops with total distance 13 963m during which is the maximal altitude difference is 182m between stops Palmovka and Krejcarek. In the first part of the line from Petriny altitude is practically only decreasing until location 6976m for start point, which is Vltavska stop. After this track have one altitudinal oscillation and then it increase dramatically between tram-stops Palmovka and Krejcarek until Strazni stop. After this tram-stop track again decreasing its altitude until last stop.

As the last part of input track data is very important to have allowed maximum speed on the track. For this calculation we used acceleration $a_{used} = 1.04 ms^{-2}$, which I obtained as real value from vehicle computer during testing rides. Maximal acceleration could be about $a_{max} = 1.5 ms^{-2}$, but this acceleration is less common for obvious driver abilities and reactions and passengers comfort as well. Mostly maximum speed on different parts of track is 50 kmh^{-1}.

For more realistic data is in speed dependence included also decelerations and accelerations from, or to crossings (speed $v_{cross}=10 kmh^{-1}$) and speed limitations depending of track conditions such as curves. The highest allowed speed on this track is $60 kmh^{-1}$.

All the data we obtained we need for make an exact model of physical behaviour of tramway during ride to the hill, in the plain or from to hill. Other features of track is mostly connected with tram behaviour on the track and will be mentioned in part 4.2.



Graph 10 - Track conditions on tramway line No.1

4.2. Chosen vehicle for realisation of Simulink model

4.2.1. Basic data useful for model in MATLAB

As a main task of this work is to prove energy savings with using supercapacitor technology, I changed vehicle which is not so old, which use modern technologies of driving and is still easy to find information about it. For this project I have chosen tram type KT8D5R.N2P as an ideal technologically featured vehicle. As it is mentioned above, this tram is double-side three-part low-floor vehicle which is used on almost all Prague lines. In our model we calculate tramway mass bigger, it is because of passengers, so to nominal weight we calculate 100 people/80 kg each.

Technical parameters:		
	value	**unit**
Length	30,30	m
Weight	38500,00	kg (without passengers)
Maximum Passengers	56+171	sitting + standing passengers
Vmax	65,00	km/h
Total power	360,00	kW
Engine	45kW	8 x TE 023, DC serial excitation
Engine speed	1720	rpm
Torque	256,00	Nm
Current	175,00	A
Engine efficiency ratio	0.89	-
gear- ratio	1 : 7.36	-
wheel radius	0,35	m
ball-bearing friction coefficient	5,00	-
dry friction coefficient	0.3	-
aerodynamic friction coefficient	0.0031	-

Table 2 - Technical parameters used for tramway model in Simulink

4.2.2.Physical model of tramway and used equations

For our model interpretation we need not only information about track and tram stands alone. It is necessary as well have some information about tramway behaviour on plan track, on hill climbing or right down. This we can interpret with equation of all physics forces which we can calculate and which are changing between rides. As the best solution is to write it in equation:

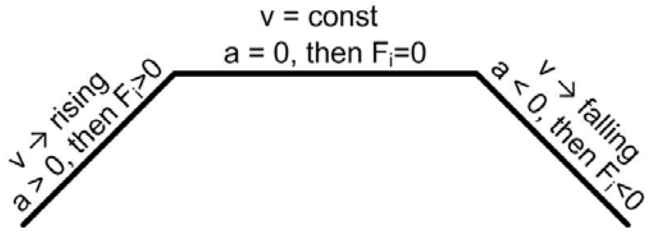
$$\sum_{i=1}^{i} F_i = 0$$

$$F_{inertia} + F_x + F_{dry\_friction} + F_{aerodynamic\_drag} - F_{eng} + F_{brake\ system} = 0$$

This detailed equation we can explain separately element by element.

Element $F_{inertia}$ represents inertial forces, which is in fact interpretation of 1.Newton law, which says that an resting object will remain at rest unless acted on by unbalanced force. An object in motion continues in motion with the same speed and in the same direction unless acted upon by an unbalanced force. This law is valid and used only when object´s acceleration is not 0. It means during acceleration or braking. Scheme we can see on Picture 19.

$$F_{inertia} = m\ddot{s}\ (where\ m - weight, \ddot{s} - acceleration)$$

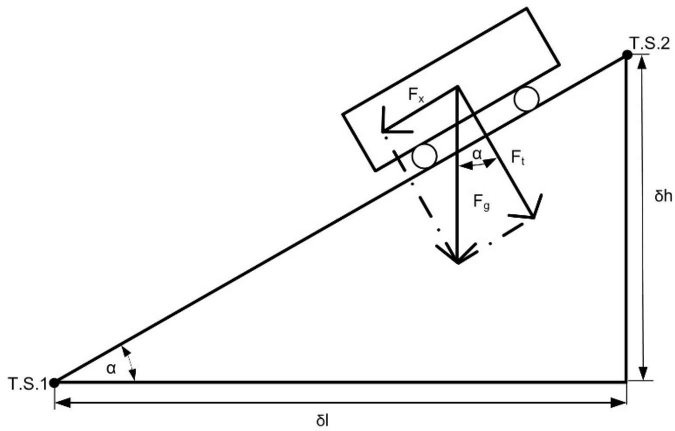


Picture 20 - Interpretation of inertial forces during tramway acceleration, constant speed ride and braking

Except of altitude is for physical tramway model very important to know also changing of angle α , which is angle between gravity force F_g and force F_x, which is the force we obtained by orthogonal projection of gravity force on tramway riding to or down the hill. Simply said, this angle interprets to or from how steep hill is tramway actually riding and from this information we can calculate how much energy it need to have wished track speed. This force we can calculate with equation

$$F_x = F_g \sin \alpha$$

F_x interpret force which brakes tramway during ride to the hill and which accelerates tramway in ride down the hill. To better understanding this force we can see illustration of model situation during ride to the hill and forces affecting the tramway.

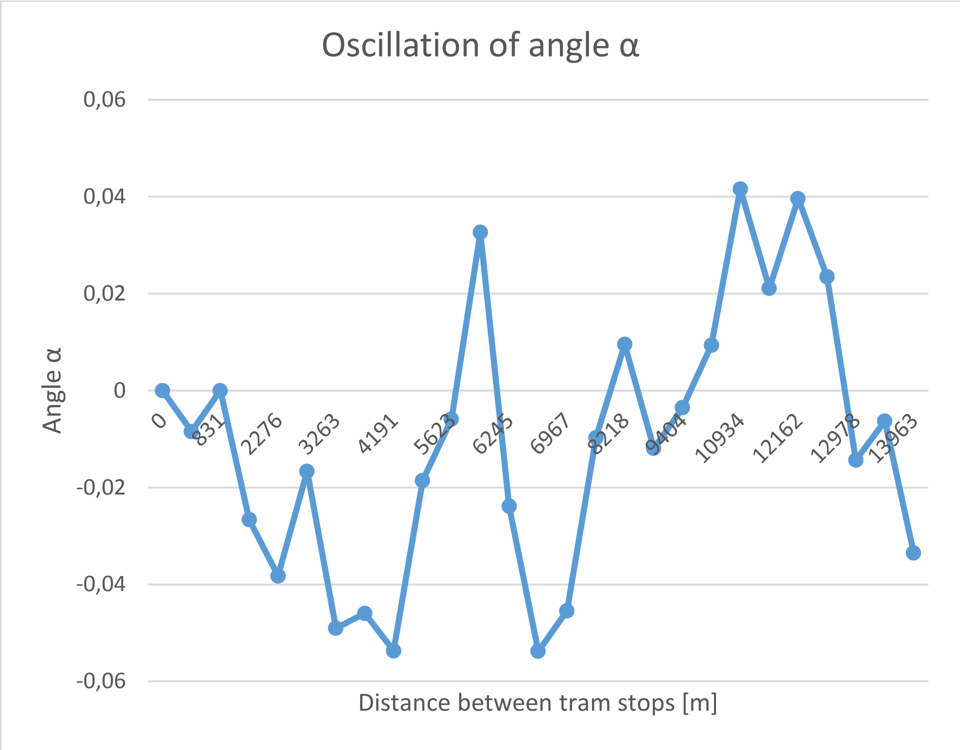


Picture 21 - Interpretation of forces and angle α in ride up to the hill

Force F_x depends on angle α, that means the force is changing in every part of or track with changing the altitude. It means that for our simulation we need to know all values of angle α in whole the track. We can easily calculate this value using basic Excel functions and right triangle laws by equation:

$$\alpha = \tan^{-1} \frac{\delta h}{\delta l}$$

It means that I calculated change of height and change of distance in every part of track line for tram No.1 and results for whole track are mentioned in Graph.11



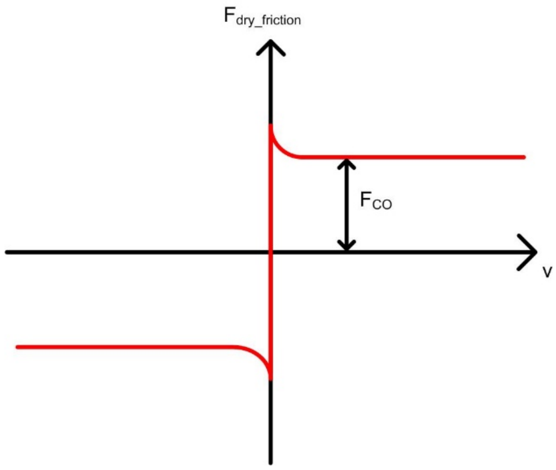
Graph 11 - Oscillation of angle α between tram stops on line No.1

Dry friction is kind of friction depends on conditions of co-work between tramway and rail. As we can see in equation below. Numbers represent constants really close to model tramway[17]. Except of constants dry friction depends on weight, which represents weight of empty tramway M_t and added mass M_p of passengers. For this calculation we use 50 passengers with average weight of 80kg. Variable g interprets gravity acceleration constant. We can start from the basic equation.

$$F_{dry_{friction}} = F_{Co} * sgn(v)$$

$$F_{Co} = a + b * v + b * v^2$$

$$F_{Co} = 5 * mg + 0.0031 * mg * v^2$$



Graph 12 - typical graph of dependence of dry friction on speed

After editing the basic formula we can reach the formula, we can use for our tramway with all the constants.

$$F_{dry\_friction} = 5.0 * 0.0031 * (M_t + M_p) * g$$ [9]

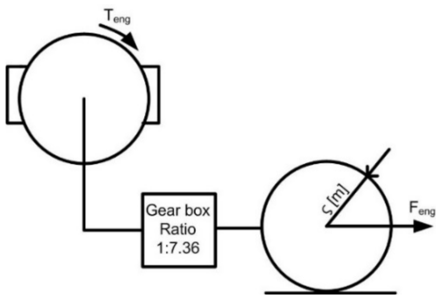
Aerodynamic drag calculating forces, which are against movement of tramway as a friction of air. As we can see in the equation below, this force depends, factually, on squared speed. It means, that by rising value of speed the bigger the friction of air is and bigger the force of aerodynamic drag is. Equation include constant μ_2 which represent dependence of weight on constants, which are different, in dependence of conformation of front and side parts of tramway. As well as in case of dry friction we use weight in empty state + weight of 50 people with average weight of 80 kg.

$$F_{aerodynamic_{drag}} = \mu_2 * |v| * v$$

$$\mu_2 = 0.0031 * 0.001 * (M_t + M_p) * g * 3.6^2$$

By Element F_{eng} we calculate force of engine. For own calculation we need to know torque of engine, radius and efficiency of engine.

$$F_{eng} = \frac{T_{eng}}{\varsigma * \eta}$$



Picture 22 - Transfer scheme of electric torque from engine to wheel (Author: Daniel Sihlovec)

Element $F_{brake\ system}$ we use only in case of brake. We can interpret this value as friction of mechanic brake system during braking. Description with equations:

$$F_p = (F_{friciton} + F_x) + F_{brake}$$

$$0 = (F_{friciton} + F_x) + F_{brake} \overset{then}{\Longrightarrow} F_{brake} > -(F_x + F_{friction})$$

It means, that force need to stop is bigger than force as orthogonal projection of gravity force on tramway in plain and friction force. We can use this force in case of small speed, when energy from engine is so small, that there is no meaning to recuperate it or to save it in supercapacitor or accumulator batteries.

4.3. Calculation of data for supercapacitor/batteries system designing

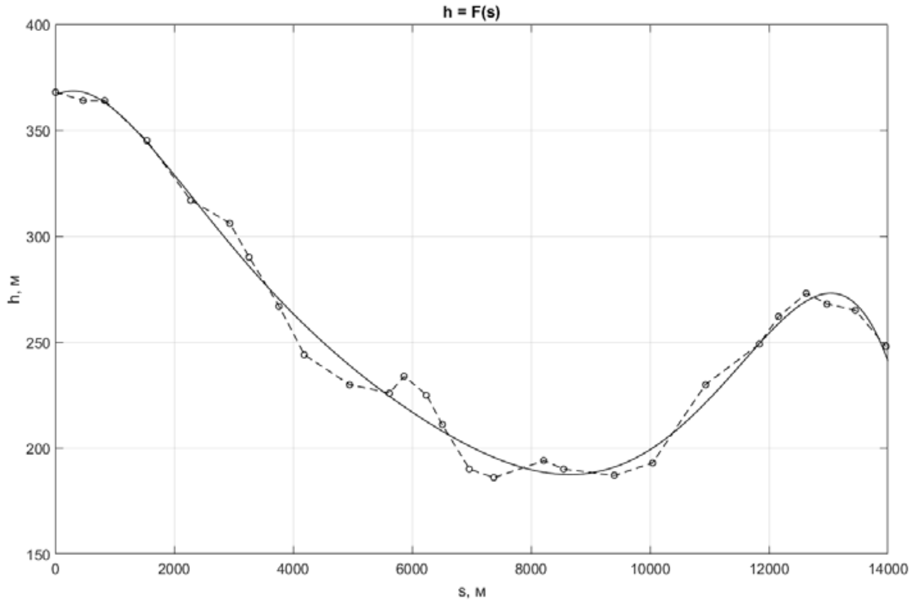
As first part of our calculations we used dependence of angle α to distance and track profile, that was mentioned in part 4.1. and 4.2.2.2. Then we simulated real distance stations, set to 27, and created in MATLAB code simulation of tramway service between these stops. These stops was set in real track profile. This profile, mentioned above was approximated into function as variable for easier use in Matlab computations:

*H(s) = - 1.9339e-21*s^6+7.4649e-17*s^5-1.1123e-12*s^4+…*
*8.2586e-09*s^3-2.993e-05*s^2+0.01593*s+366.26*

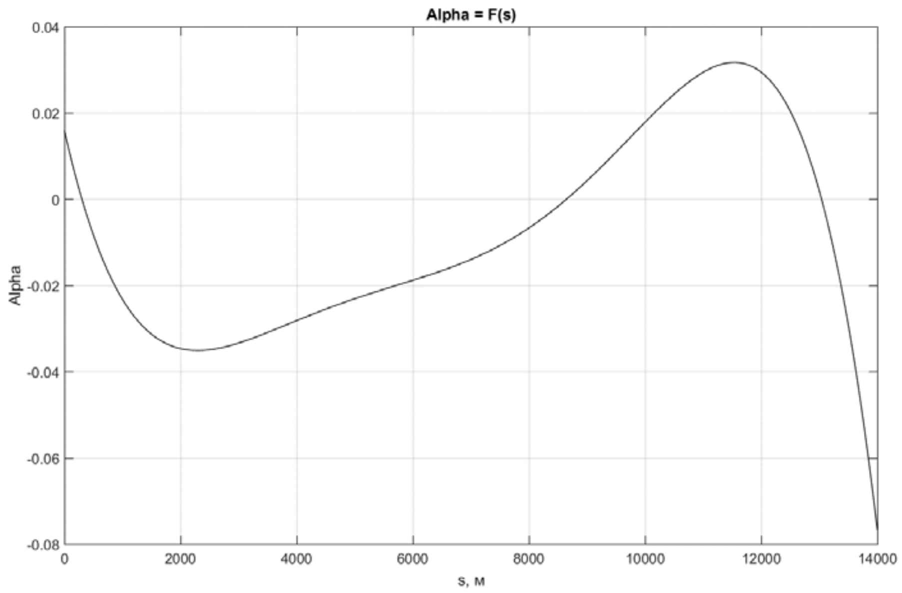
The same approximation we did with angle α:

*Alpha(s) = -1.16034e-20*s^5+3.73245e-16*s^4-4.4492e-12*s^3+...*
*2.47758e-8*s^2-0.5986e-4*s+0.1593e-1*

Approximation of these functions we put into graphical form as we can see on graphs 13 and 14. We used polynomial approximation of 6th order to approximate dependence of distance with altitude and polynomial approximation of 5th order. This was enough to have function which is quite near to all our values and easy enough to use in quick calculations in Simulink.

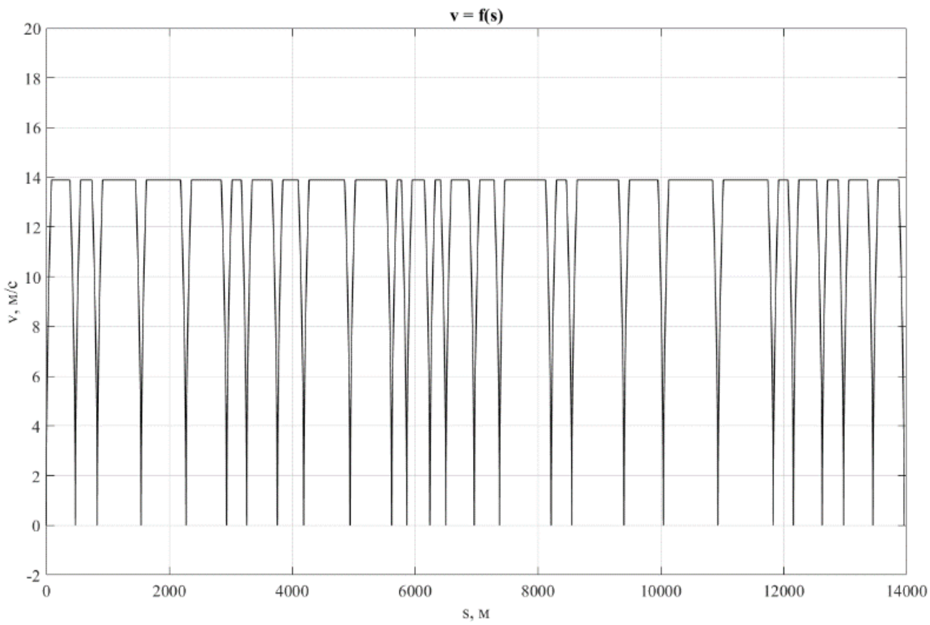


Graph 13 -Approximation of track profile into function H(s)



Graph 14 - Approximation of track angle change into function Alpha(s)

For simulating the trajectory of my tramway line, is necessary to define it. It means, that when I use approximated distance of 14 kilometres and divide this distance into 27 tram stops, the distance between two tram stops will be according to real data. In these distance I have 4 modes of tramway service. There is accelerating mode, constant speed ride mode, braking mode and tram stop. Acceleration is set up constant between acceleration mode and braking mode a=1.1ms^{-2}. In every this part we use actual values by dividing this part into 1000 pieces to interpret time derivation.



Graph 15 - Speed of tramway between fictive tram stops

As next step it was necessary to calculate force characteristics in dependence to distance. We applied equation given above for every single step (n) for:

- Accelerating and braking mode:

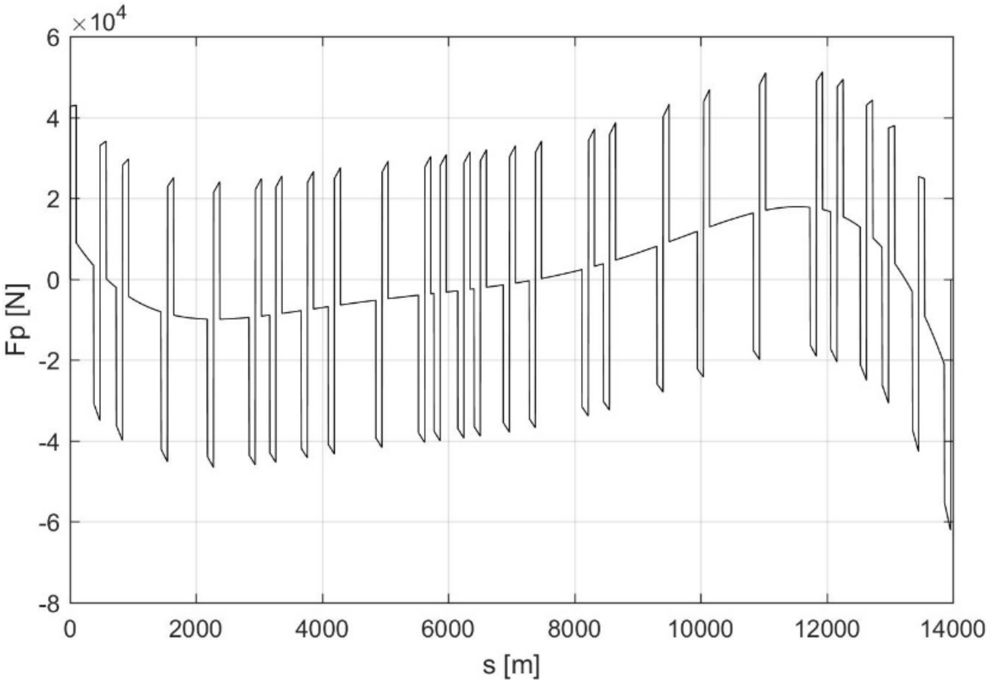
$$F_{part_1+3}(n) = F_{inertia}(n) + F_x(n) + F_{dry\_friction}(n) + F_{aerodynamic\_drag}(n)$$

- Constant speed ride:

$$F_{part\_2}(n) = F_x(n) + F_{dry\_friction}(n) + F_{aerodynamic\_drag}(n)$$

We can see, that only difference between calculations is missing inertial force in constant speed ride. It is caused by fact that inertial force is in dependence of acceleration value. It means that if your tramway is riding on constant speed, acceleration value is zero. On graph 16 there is characteristic of force in the whole distance of tramway service on line No.1. Values above the line of angle α is force, which is used for accelerating, values bellow is the same value force as in first case, but this have opposite orientation and is used for brake the tram. Showed calculation is only for one part of one mode, if we would like to calculate force for the distance between two stops we can use this equation:

$$\sum_{i=1}^{n} 2 * F_{part\_1+3} + F_{part\_2}$$

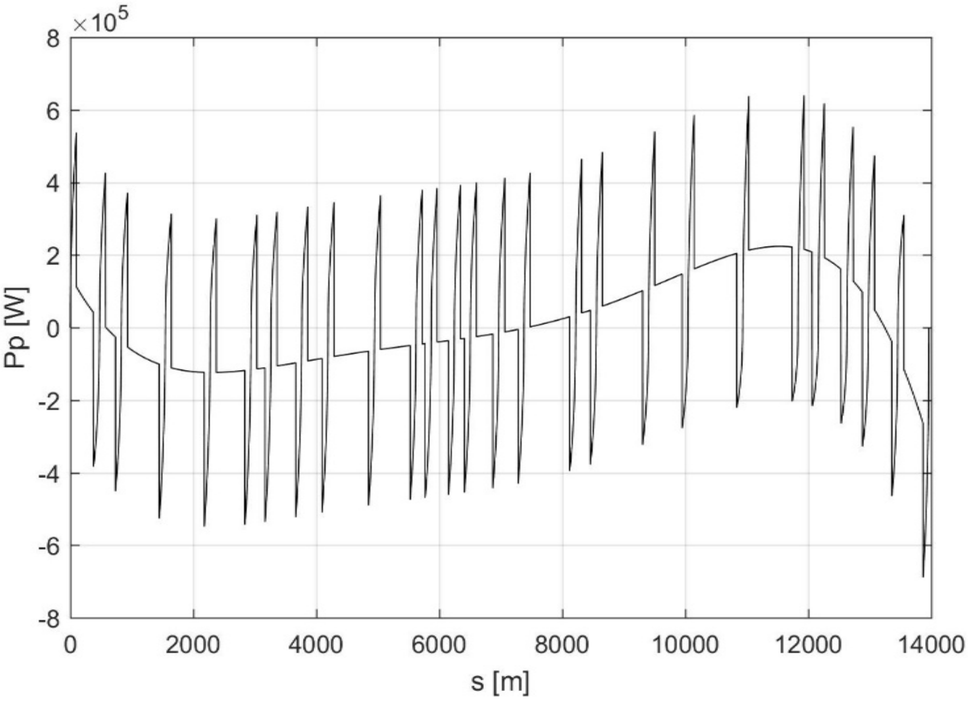


Graph 16 – Function force on distance calculated between stops

Semi-final step is to calculate all the power used for tram service in the whole distance of our line No.1. After calculating the force used for it, is the basic calculation really easy. It depends only on force, used in exact "n" part and speed which is due to the forced part.

$$P_{part}(n) \ = \ F_{part}(n) * V(n)$$

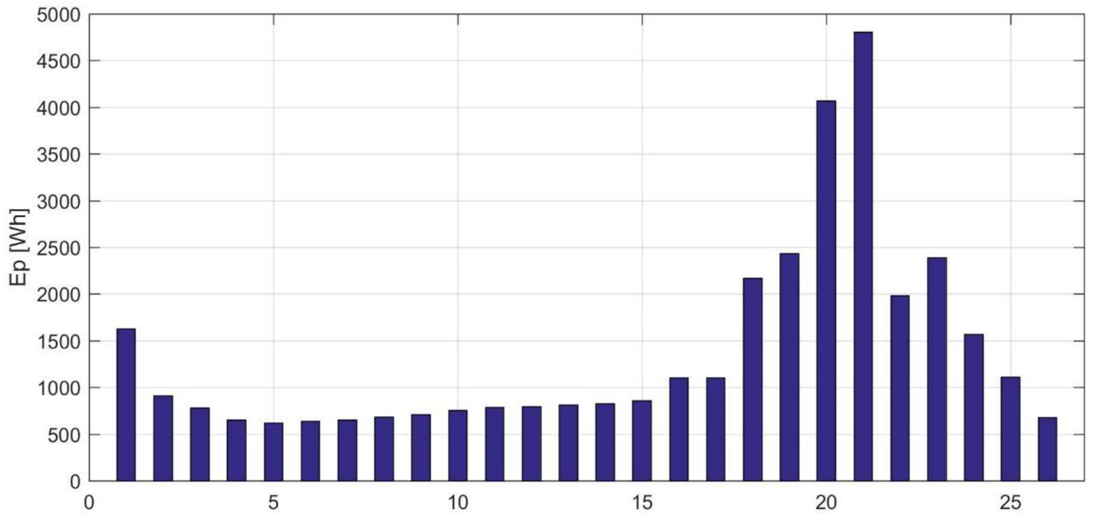
Next method is totally the same as in previous case. All the calculations are given in the graphical characteristics on Graph. 17. Interpretation of data is pretty close to Graph 16. All the data above the angle α characteristics are used for acceleration and all the data bellow that, are used for braking the tramway.



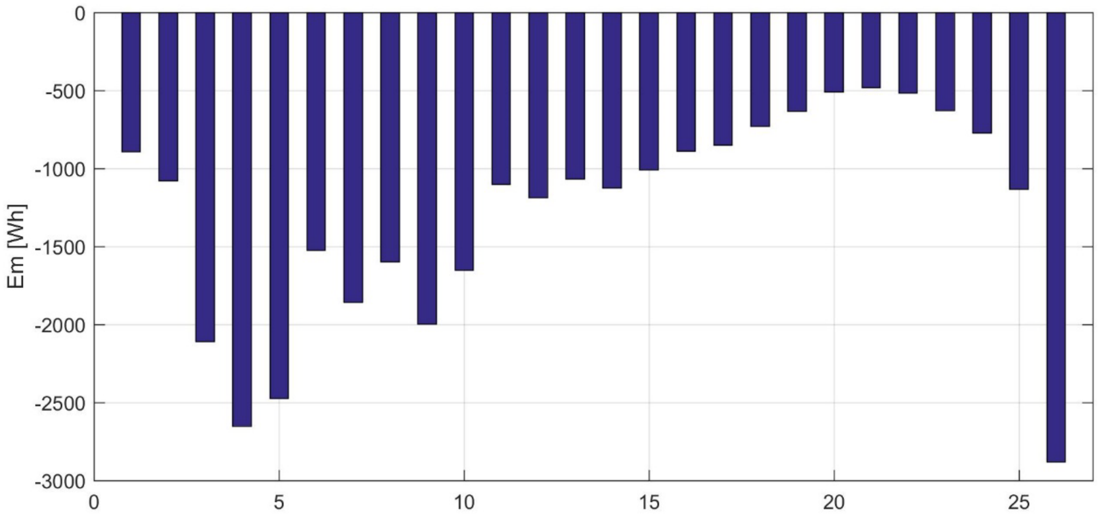
Graph 17 - Power calculated between tram stops

After the last calculation we can see the basic results of tram service on surveyed line. For managing the design of appropriate supercapacitor or accumulator battery system we need to know mount of energy, which is used for accelerating and mass of energy, which is made during braking process. Especially for this is programme developed to differ these two energies and draw two different graphs. Energy of exact distance between n^{th} tramstop we can calculate as time by which was used exact amount of power. Equation given bellow.

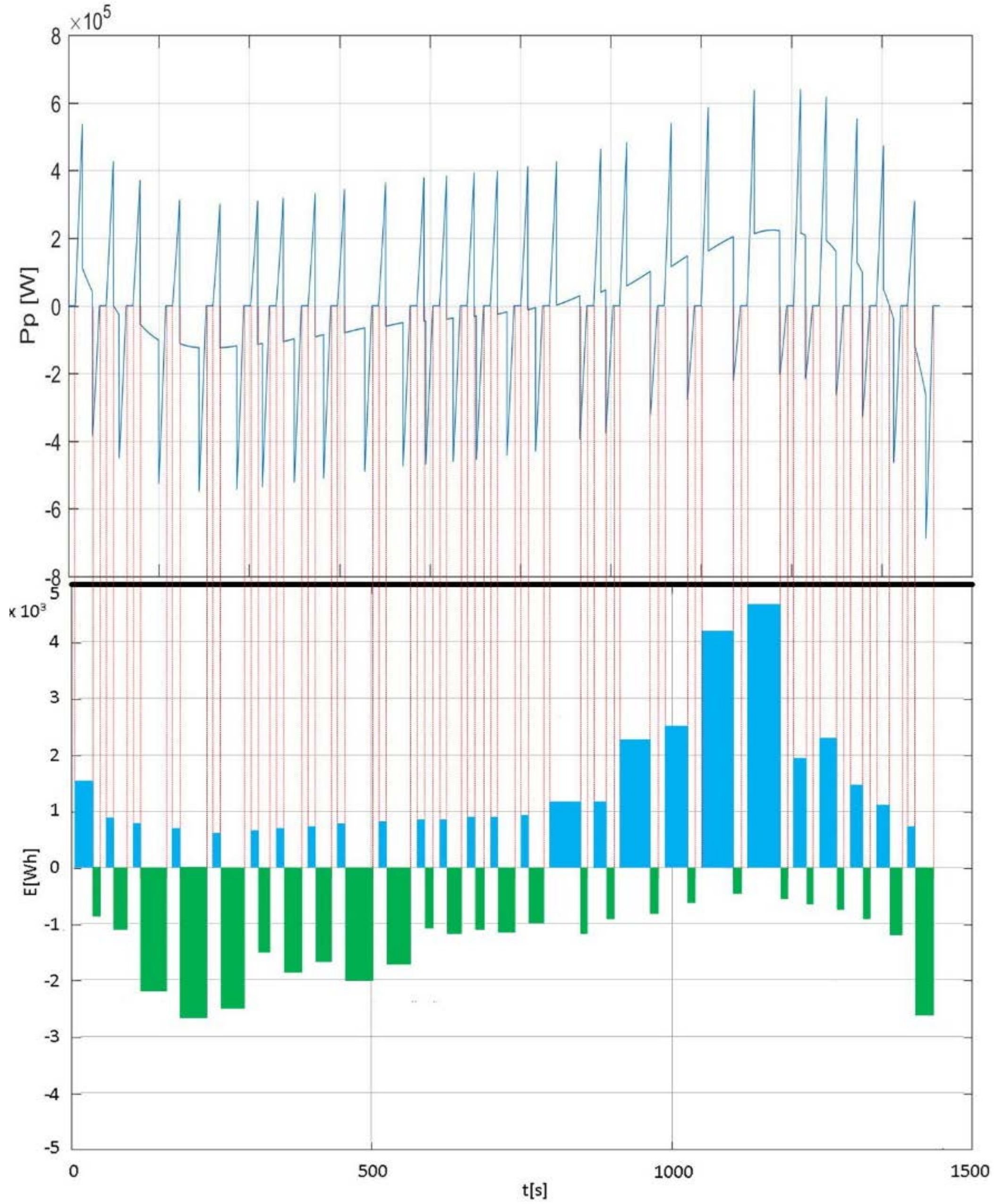
$$E_{part}(n) = P_{part}(n) * t(n)$$



Graph 18 - Energy used between tram stops in dependence on time



Graph 19 - Energy which we can save during tramway ride on Line No.1



Graph 20 - Projection of power spend in time into Energy (blue - we need to accelerate tram, green - energy we can spare)

From the Graph 18, Graph 19 (above) and Table 3 (below) we can read all the data about energy consumption/ manufacturing in time of service between stops.

Interpretation of this data we can see in Graph 20, where is projection of power (higher part of graph) during time into energy (lower part of graph). All the energy that is blue coloured is energy which is spent for acceleration and ride to hill. All the green coloured energy is energy we can save into our accumulators.

4.4. Designing of supercapacitor/accumulator batteries hybrid system

In this part I would like to design three different types of alternative power source system. First one is system using only supercapacitors as an accumulator bank. Second one is system which is built only from accumulation Li-ION batteries and the last one case is system which is mixture of half supercapacitor and half Li-ION batteries system.

4.4.1.Calculation of energy density of accumulation energy system

4.4.1.1. Variant with biggest value of spared energy on track

All the data received from calculations gave us all the information about consumption of energy used for drive and manufactured energy which is nowadays spent in resistors or given back to supply system during recuperation. As it is written before, we can use this energy more effectively. In table below we can see all the energy management data from tramway ride from the first to the last stop. These data are transformed in 2 ways and it is in Joules and kWh. I used transformation ratio:

$$1\,J = 0.000277778\,Wh$$

First possibility of design is to choose exact energy density of designed system, to find the biggest value of energy that can be stored. As we can see in bold letters, it is in Table 4. This value is 7192691,825 J which is equal to 1,99787155 kWh. For comparison of energies used for tramway ride we can check energy use for accelerating of tram on the whole track in Table 3.

TRACK PART	E_{USED} [J]	E_{USED} [WH]
1	5865810,527	1629,393117
2	3278149,634	910,597849
3	2823339,845	784,2616955
4	2339947,37	649,9859005
5	2223497,527	617,6386959
6	2291393,221	636,4986261
7	2353801,207	653,8341917
8	2463272,725	684,242971
9	2558220,554	710,6173889
10	2710582,351	752,9401444
11	2829639,984	786,0117356
12	2871227,444	797,5638168
13	2937242,919	815,9014636
14	2986208,409	829,5029993
15	3085349,714	857,0422729
16	3967342,171	1102,040374
17	3973375,894	1103,716409
18	7806358,611	2168,434682
19	8761053,121	2433,627814
20	14643515,98	4067,646581
21	17290854,5	4803,018981
22	7137765,305	1982,714171
23	8607156,202	2390,878636
24	5644645,237	1567,958265
25	4011399,225	1114,278454
26	2450094,493	680,582348

Table 3 - Energies spent during ride of all parts of ride

TRACK PART	E_{STORED} [J]	E_{STORED} [WH]
1	-3209063,379	-891,4072072
2	-3876321,171	-1076,756742
3	-7584626,229	-2106,842305
4	-9538060,099	-2649,463258
5	-8903361,57	-2473,15797
6	-5487410,597	-1524,281941
7	-6684102,342	-1856,69658
8	-5755615,843	-1598,783458
9	**-7192691,825**	**-1997,97155**
10	-5950367,761	-1652,881256
11	-3966478,852	-1101,800563
12	-4276331,576	-1187,870833
13	-3834707,324	-1065,197331
14	-4042315,198	-1122,866231
15	-3629860,697	-1008,295445
16	-3198944,585	-888,596429
17	-3057132,41	-849,2041265
18	-2628010,142	-730,0034012
19	-2268055,041	-630,0157931
20	-1834608,915	-509,6139953
21	-1726752,417	-479,6538328
22	-1849773,504	-513,8263843
23	-2253877,085	-626,0774689
24	-2777800,267	-771,6118026
25	-4077357,451	-1132,600198
26	-10370959,69	-2880,82444

Table 4 - All energies, we can save on line No.1 ride

4.4.1.2. Variant with calculating use of saved energy managed by demand

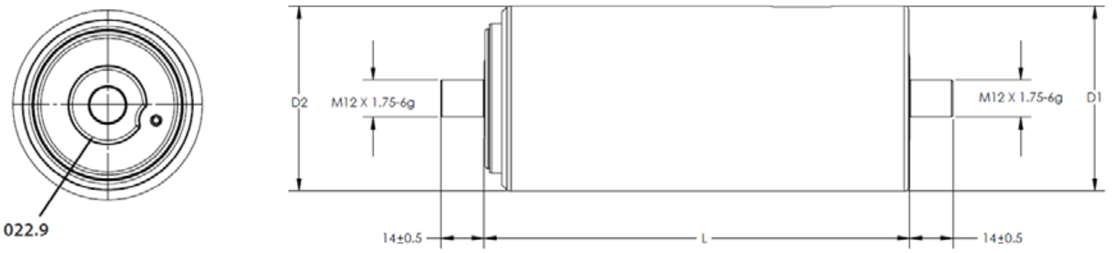
This variant is more specific and little bit more complicated for calculations but it is managed to be more economic by choose of the exact variant of supercapacitor. This supercapacitor is chosen by calculation which considers, that not all of energy saved in supercapacitor could be spent in one moment and there is a possibility that some of the energy could stay in supercapacitor. By this we use equation which is based on simple steps.

After first acceleration of first ride between tram stops we start to save energy during braking process. We spare some energy and this energy we use to acceleration. However, the saved energy value is bigger than energy demand for acceleration. It means, that some energy stand in supercapacitor. This energy is not going to lose somewhere and stay there as electrostatic capacity. During next brake mode, we save more energy to that, we saved before and our reserve for next acceleration is bigger. In case of acceleration to the steeper hill in that we use all the energy saved in supercapacitor, during next braking process we save again exact energy which is made in process of electro-dynamic braking.

4.4.2.Designing or stand-alone supercapacitor system

For our task of designing of supercapacitor I have chosen a supercapacitors from company MAXWELL. In designing task is important to consider more factors from the most important such as energy density, life cycles, rated voltage, dimensions or weight. On the Picture 23 and Picture 24 we can see basic datasheet from company Maxwell. All the products which are mentioned in the tables are just for one supercapacitor and we need to calculate how much of them we need for our energy savings. For this condition is appropriate to choose the best possible value of capacity in comparison to weight to have the best conditions in weight, energy, number of supercaps interconnected in one system and dimensions.

DIMENSIONS



Part Number	Volume	L (±0.3mm)	D_1 (±0.2mm)	D_2 (±0.7mm)
BCAP0650 P270 K04 02	0.211 L	51.5 mm (±0.5mm)	60.4mm	60.7mm
BCAP1200 P270 K04 02	0.294 L	74 mm	60.4mm	60.7mm
BCAP1500 P270 K04 02	0.325 L	85 mm	60.4mm	60.7mm
BCAP2000 P270 K04 02	0.373 L	102 mm	60.4mm	60.7mm
BCAP3000 P270 K04 02	0.475 L	138 mm	60.4mm	60.7mm

PRODUCT SPECIFICATIONS

CAPACITANCE	BCAP0650	BCAP1200	BCAP1500	BCAP2000	BCAP3000
Nominal capacitance	650 F	1,200 F	1,500 F	2,000 F	3,000 F
Tolerance capacitance	-0% / +20%	-0% / +20%	-0% / +20%	-0% / +20%	-0% / +20%
VOLTAGE					
Rated voltage	2.7 V DC	2.7 V DC	2.7 V DC	2.7 V DC	2.7 V DC
Surge voltage	2.85 V DC	2.85 V DC	2.85 V DC	2.85 V DC	2.85 V DC
Maximum operating voltage			N/A		
RESISTANCE					
ESR, DC Max., room temperature	0.8 mΩ	0.58 mΩ	0.47 mΩ	0.35 mΩ	0.29 mΩ
ESR, 1khz (Max.)	0.6 mΩ	0.44 mΩ	0.35 mΩ	0.26 mΩ	0.24 mΩ
TEMPERATURE					
Operating temperature range Stored uncharged	-40°C to +65°C	-40°C to +65°C	-40°C to +65°C	-40°C to +65°C	-40°C to +65°C
Storage temperature range Cell case temperature	-40°C to +70°C	-40°C to +70°C	-40°C to +70°C	-40°C to +70°C	-40°C to +70°C
POWER					
Pd	6,800 W/kg	5,800 W/kg	6,600 W/kg	6,900 W/kg	5,900 W/kg
Pmax	18,900 W/kg	15,900 W/kg	18,500 W/kg	19,400 W/kg	14,800 W/kg
ENERGY					
Emax	4.11 Wh/kg	4.67 Wh/kg	5.42 Wh/kg	5.63 Wh/kg	5.96 Wh/kg

Picture 23 - Datasheet of MAXWELL supercapacitors

PRODUCT SPECIFICATIONS (cont.)

DC LIFESPAN	BCAP0650	BCAP1200	BCAP1500	BCAP2000	BCAP3000
Endurance At rated voltage and 65°C.	1,500 hours	1,500 hours	1,500 hours	1,500 hours	1,500 hours
Capacitance change % of rated value	≤20%	≤20%	≤20%	≤20%	≤20%
Internal resistance change % of rated value	≤60%	≤60%	≤60%	≤60%	≤60%
Life test At rated voltage and 25°C.	10 years	10 years	10 years	10 years	10 years
Capacitance change % of rated value	≤20%	≤20%	≤20%	≤20%	≤20%
Internal resistance change % of rated value	≤100%	≤100%	≤100%	≤100%	≤100%
CYCLE LIFE					
Cycles Between specified voltage and half rated voltage under constant current at 25°C.	1 million	1 million	1 million	1 million	1 million
Capacitance change % of rated value	≤20%	≤20%	≤20%	≤20%	≤20%
Internal resistance change % of rated value	≤100%	≤100%	≤100%	≤100%	≤100%
SHELF LIFE					
Shelf Life Uncharged over storage temperature	2 years	2 years	2 years	2 years	2 years
Capacitance change % of rated value	10% decrease	10% decrease	10% decrease	10% decrease	10% decrease
ESR change % of rated value	50% increase	50% increase	50% increase	50% increase	50% increase
CURRENT					
Maximum continuous current	62 A	81 A	97 A	123 A	147 A
Maximum peak current, 1 sec	575 A	955 A	1,185 A	1,585 A	2,165 A
Leakage current, I_{LC} After 72 hours. Initial leakage current can be higher.	1.5 mA	2.7 mA	3.0 mA	4.2 mA	5.2 mA
CONNECTION					
Terminal	Threaded or Weldable				
SIZE					
Dimensions (L x W x H) (mm)	See drawings				
Weight	0.16kg	0.26kg	0.28kg	0.36kg	0.51kg

Picture 24 - More datasheet information of Maxwell capacitors

For appropriate and economical design of supercapacitor we need to know how much energy we need to store in it. I have chosen the second possibility and that is a variant with saved energy and use of energy by demand.

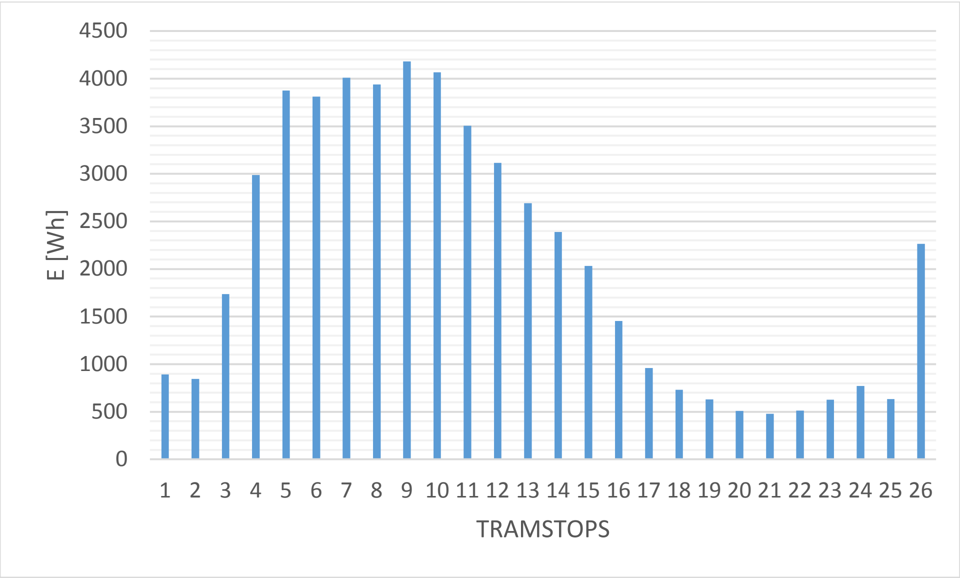
As first it was necessary to calculate, what is the biggest value of energy, we can save in supercapacitors using this method.

$$E_{rest} = E_{saved} - E_{used} \text{ then } E_{rest_1} = E_{rest} + E_{saved_1} - E_{use_1} \dots$$

For this application is the biggest value of saved energy E_{SE}=4181.654 Wh, which means that our accumulator system based on supercapacitors have to be able to save this energy as we can see in the Graph 21. When we know the exact value we can continue in our calculations into calculation of exact number of supercapacitors. In MAXWELL datasheet was chosen the supercapacitor with biggest value of capacitance and it is BCAP3000. By knowing all the information as rated-voltage, capacitance and current we can calculate energy of one supercapacitor by using:

$$E_0 = \frac{1}{2}CU^2$$

where we use as rated voltage 2.7 V and maximum capacity 3000 Farads. From this calculation we received value of E_0=10935 J, which is about 3,037 Wh. Dividing value of E_{SE} by value of E_0 we reached the final value of supercapacitors for our application in tramway. We need 1393 pieces of it in our system. For easier calculations we can accept number of pieces between 1377-1400.



Graph 21 - Saved energy in supercapacitors managed by demand

These supercapacitors should be properly interconnected between each other to have ideal energy and power. The more series interconnections there are, the bigger is voltage of system and final energy. The more parallel branches there are the bigger is current flowing through it and as well power. For ideal parameters is best way to find compromise between parallel and series interconnections satisfying these conditions:

$$100\,V < U_{work} < 300\,V\,;\ \ I_{BCAP3000\_Max} = 147A$$

$$U_C = \frac{1}{C}\int_0^t i_C\,dt \text{ then for DC system } U_c = \frac{1}{C} I_C t$$

$$E = \frac{1}{2} C U_C^2$$

The calculation of supercapacitor interconnections should be done combinatorically. Try to find the best mixture of supercapacitor interconnection's properties. These calculations I did in Excel with combination of ten most suitable serial number of serial connected supercapacitors interconnected to one number of parallel connections. For this application I calculated 10 values of serial connections to all 13 to 37 parallel connections. I started from number 13 because 12 branches multiple by maximal serious connection of 111 supercapacitors (299.7V) is only 1332 pieces, which is not enough for our system.

These numbers are done from the fact of maximal and minimal voltage and power, which couldn´t be reached if the value of parallel connections will be higher or lower. By using conditions about voltage I could use from 38 supercapacitors interconnected in series, which give a value of 102.6V which is minimal to reach the condition of voltage to 111 supercapacitors connected in series which gives a value of 299.7V.

To these values of serial connections I fitted parallel connections which could give in system nearly 1393-1400 supercapacitors and as best result, that reached the conditions and have the biggest value of power is N_s=50 supercapacitors in series interconnection of N_p=28 branches of parallel connection.

Total number of supercapacitors used in system is 1400 and total power is 555.56kW calculated by formula:

$$P_{total\_DC} = U_{SC\_total} * I_{SC\_total}$$

The value of maximal energy, that could be saved in ride is only 80% of calculated value. That is caused by using of approximate mixture of coefficients of all possible loses.

4.4.3.Design of system using batteries

Second possibility of alternative power source system is use of batteries. All the pros and cons of batteries are mentioned above. Basic calculations are the same as in case of supercapacitors. We have value of total saved energy E_0= 4230,036 Wh and value of energy that can be saved to battery. Battery chosen for this applications is battery LT-LFP300 manufactured by Liotech, Novosibirsk, Russia. Its energy is E_{bat}=320 Wh (we reached these data by calculating of battery capacity of 200Ah multiplied by voltage of 3.2 V). If we divide these two values we realize, that we need to have 13.2188 pieces of battery, so in next calculations we are going to use an amount of 14.

The voltage of this series interconnected system is 44.8V which is alone acceptable, but because of current value only 200A we reach really low power. For this case it was added another 5 parallel branches, so the final value of parallel branches is 6 and this caused 6 times higher current and as well almost 6 times higher power.

4.4.4 Design of hybrid system using batteries and supercapacitors

For designing of this hybrid system is used both technologies and its advantages to spare energy, energy density and quantity of energy flow. As the biggest advantage of supercapacitors, we can use in this case, is its huge power density, which is much more times better then in batteries. And the same situation is with batteries, which have better energy density.

For this case I realised, that best solution will be to design a system which consist a half of all calculated amount of supercapacitors and half of batteries that are needed for it and detect, if this system could give as much energy as the alternative power source in tramway on its service on tram line No.1 will be enough.

Parameters of supercapacitors and batteries are the same as in previous cases that means that supercapacitors have capacity 3000F and batteries capacity is 200Ah. By calculating this variant I tried to find a variant which is the most suitable by energy density, power density, by mass and space requirements and of course by economic costs.

By our calculations we reach as suitable variant to use 350 pieces of supercapacitors interconnected into 14 branches with 25 pieces connected in series and 21 battery pieces. These batteries are divided into 3 parallel branches with 7 series connections. Total energy density in this designed system will be 15.33 kWh and total power density will be 152.35 kW that we can interpret as acceptable due to our biggest energy savings of about 4 kWh and the power of about 152 kW could give us appropriate system charge time and possibility of spare all energy that is made during braking process.

4.4.5 Compare of all designed solutions of alternative power source

I would like to compare all the designed technologies by technical parameters with their advantages and disadvantages and choose one the most suitable for application in praxis. All the data we can see sorted in Table 5, from which we can easily make any conclusions.

	SUPER-CAPACITORS	BATTERIES	HYBRID SYSTEM	
PARALLEL BRANCHES	28	6	Supercap 16	Battery 8
SERIES CONNECTIONS	50	14	Supercap 25	Battery 7
CURRENT - PARALLEL BRANCHES	4116 A	1200 A	Supercap 2352 A	Battery 1600 A
VOLTAGE - SERIES CONNECTIONS	135 V	44,8 V	Supercap 67,5 A	Battery 22,4 A
POWER_TOTAL	555,56 kW	53,76 kW	194,6 kW	
ENERGY_TOTAL	7,59 kWh	53,76 kWh	37,738 kWh	
MASS_TOTAL	714 kg	798 kg	736 kg	

Table 5 - Parameters of APS system

If we are comparing in case of power density, the best possibility is to choose a system based only on supercapacitors, but we already know, that this value means only: “How big can be flow of energy into supercapacitor”. For us is important as well energy density which is better in case of battery using system. Problem of only batteries system is low power, which means by dependence of energy and power, that this energy saving system could charge and feed drives much longer then supercapacitor system. If we compare by the parameter of weight we can see that the both systems with their amount of accumulators are approximately the same about 800 kg for the system.

Hybrid system using both variants of technologies can have both advantages from supercapacitors and batteries system in one as well as energy density and power density. If we look in the Table 5, we can see that total energy of hybrid system is lower than in case of batteries, but much higher than in case of supercapacitors and otherwise, power density of hybrid system is lower than in case of supercapacitor system, but about 3 times higher than in only battery system.

For use in tramway is energy density enough, because of our calculations, the highest value of energy that we can save is almost 4.2 kWh, that means our 37.738 kWh is enough.

$$E = P * t$$

By using formula above we can calculate as well time that we need to charge our system on value that we need. In case of our hybrid system is this value 77.69 s which is value for acceptable for use in public city transport in according to longer distances between tram-stops and longer times to stop tram riding down the hill.

Factor which is as well important as energy and power densities is weight of saving system. If we compare only this system without any converter and we take weight parameters of 0.51 kg for one piece of supercapacitor and 9.5kg for one battery, we can see in the Table 5 that hybrid system is more appropriate not only by density, which could be given in the same weight. Total weight can influence energies need to accelerate, friction or aerodynamic drag, but the difference is, how much energy we can get from this mass and that is in case of hybrid system better.

If we compare all this information together and we are considering in technic parameters is the most suitable hybrid system using as well batteries as supercapacitors.

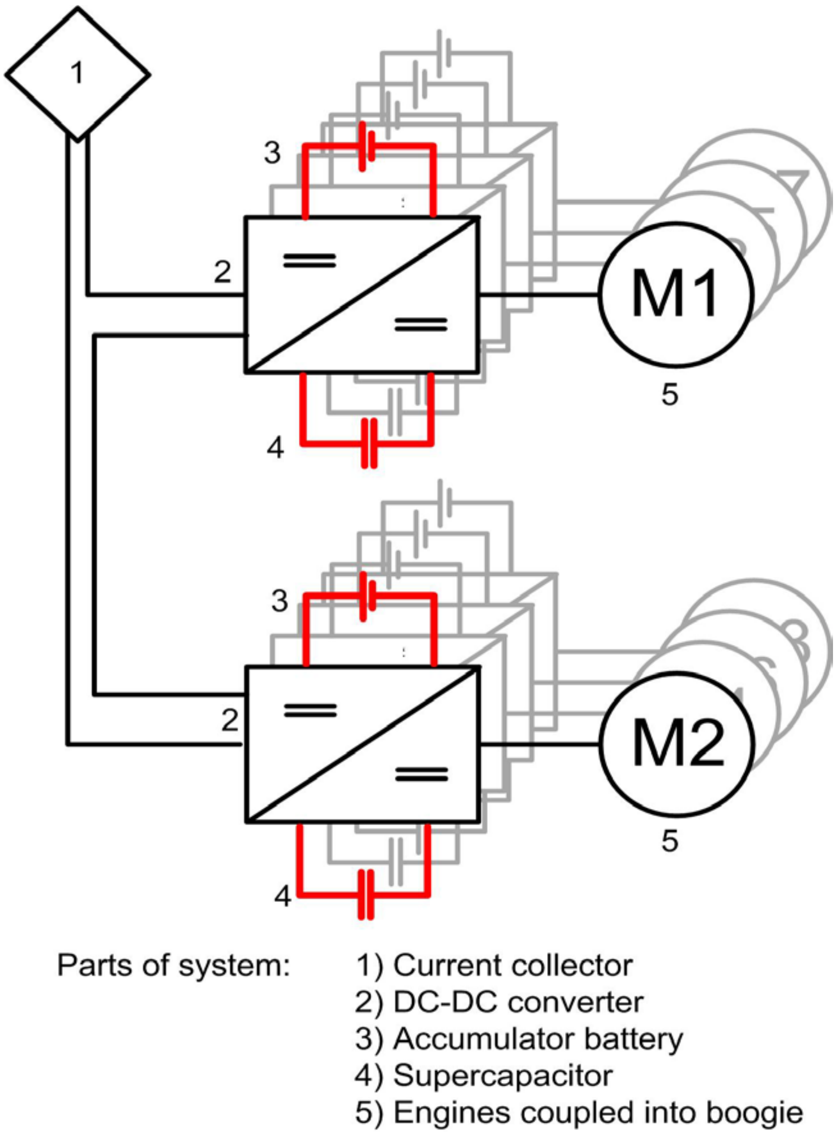
5. Simulink model

5.1. General model using APS in scheme

There are more possibilities how to connect alternative power sources into system. For example, we can develop whole accumulating system as one case with supercapacitors and batteries or separated system with supercapacitors and separated with batteries. This variant is for feeding all the system simultaneously. The main threat of this system is to design and construct system and feeding cables appropriate for current flowing from engines, through converters directly to our saving system. Tram KT8D5R.N2P consists 4 boogies with total 8 DC-engines, which means that in case of 100 A current flow ,made during braking, on one engine, total current flowing into converter and saving system will be little bit under 800A (we consider losses in cables and converter). Maximum current of TE.023 engine used in tram type KT8D5R.N2P is 250A. Automatically, current into APS system grows 8 times on value 2000 A and this value we have to consider in our calculations and designing the system.

We can use system specifications used in tram model nowadays. Every boogie has its own converter, which is in fact two coupled converters in series, for each engine one. According to this system arrangement is more appropriate variant to equip every converter its own APS system consisting accumulator batteries and supercapacitors as we can see on Picture 25.

Interconnection between two converters on one boogie is chosen serial. This is caused by request on lower voltages on every converter. If supply voltage is 600V that means the voltage on every converter coupled on one boogie is 300V. Losses on IGBT switching features, which are mostly used in power electronics for transport, are in dependence to voltage and current and as well to resistance. The lower voltage allow us to use as well unipolar transistor type, where the losses are in dependence $R_{MSFT} \sim U^k$ and where we can downgrade resistance by downgrading the voltage.



Picture 25 - APS system settlement into traction system of tram

If we consider system arrangement with 8 engines on the whole tramway for designing is the most appropriate variant to implement into system exact number of accumulator batteries and supercapacitors into branches possible to divide by 8. According to the paragraph 4.4.5. we used 16 supercapacitor branches and 8 battery branches, which is two supercapacitor and one battery branch for single engine.

System designed the way of APS feature for every single engine have more advantages, such as economic savings on designed cable cross-section, easier diagnostics of failures or easier service. As disadvantage could be given a fact that controlling of the whole system will be more complex, but on the other hand, this ability can be used in case of failures as possibility to disconnect only broken boogie APS and not the whole system.

5.2. Mechanic model of tramway

As heart of mechanic model of tramway we use embed system “TRAM” with calculations of all forces. This embed system have on input angle “α”, feedback speed “v”, traction force “Fp”, and brake force “Fb”.

Basically we use formula for all the forces that can affect tramway ride. This formula contains inertial forces, projection of gravity force on tram riding on hill with definite angle, friction dry and aerodynamic drag and finally in the end force of brake system and force supplied by engine.

$$F_{inertia} + F_x + F_{dry\_friction} + F_{aerodynamic_{drag}} - F_{eng} + F_{brake\ system} = 0$$

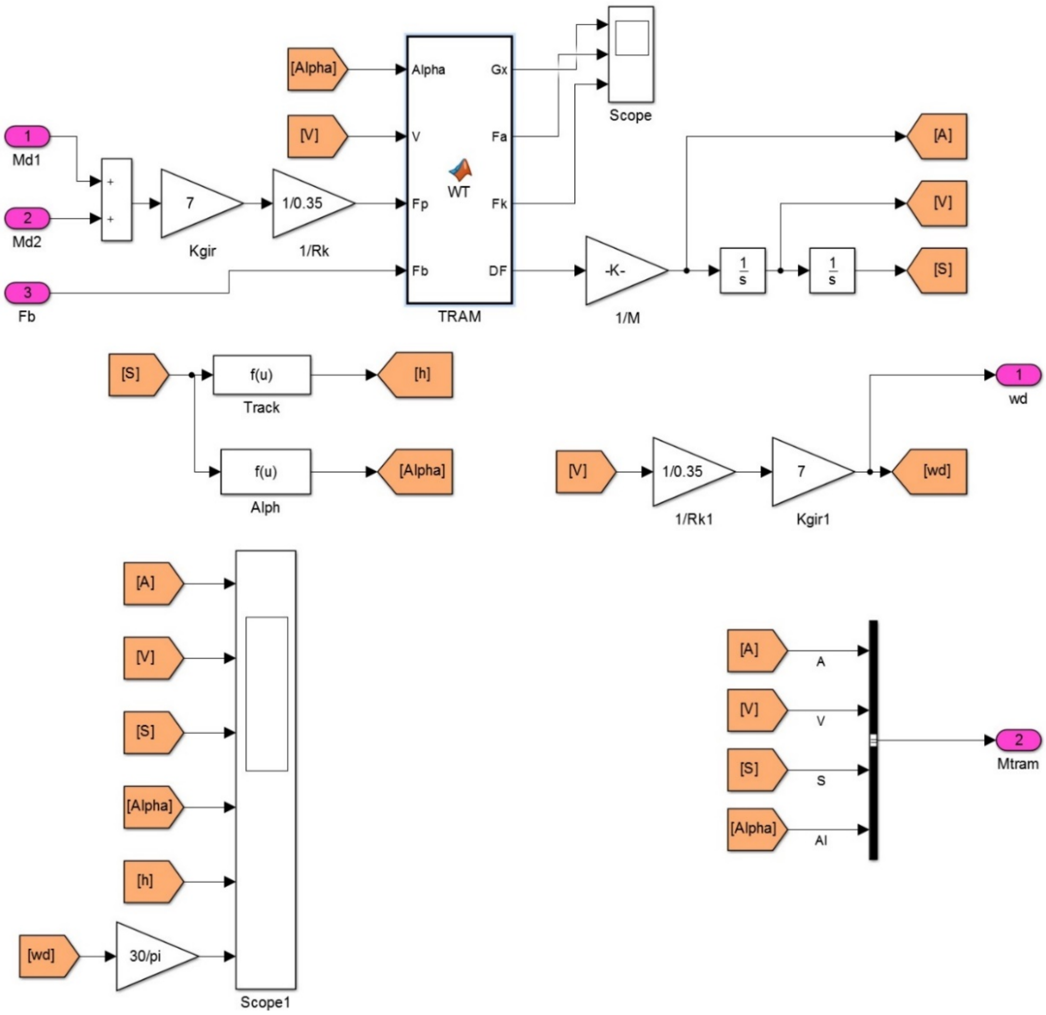
$$m\ddot{s} + F_x \sin\alpha + F_{dry\_friction} + F_{aerodynamic\_drag} - F_{eng} + F_{brake\ system} = 0$$

$$\ddot{s} = \frac{1}{m} F_{eng} - F_x \sin\alpha - F_{dry_{friction}} - F_{aerodynamic\_drag} + F_{brake\ system}$$

To easier interpretation of this equation we changed formula in way that we are calculating $\ddot{s}$ marked as acceleration. In fact this value is our output from system Box “TRAM” after multiplying the output value of “DF” by constant $\frac{1}{m}$. For reaching the actual values of speed and distance we use Integrator feature and integrate value of $\ddot{s}$ by $\frac{1}{s}$ to $\dot{s}$ that is interpreted as speed and one more time integrated by $\frac{1}{s}$ we reach s that is distance. As a feedback we use final value of distance according to height and angle alpha, that we can reach actual track conditions that are important for exact forces affect on tramway.

Output of system contains four values that are important for electrical system requirements and that is acceleration, speed, distance and angle. In Matlab we can pack these four values into one output source and then connect it directly to electrical part. Second output value is angle ω that we can interpret as angle speed.

This mechanic interpretation of actual track data and tramway conditions is very important to model and design, how much energy we need to give to accelerate tramway according to forces that are affecting it in actual time or how much energy we can save in actual position with angle on track during braking process. Model of whole mechanic system we can see on the Picture 26.



Picture 26 - Mechanic model of tramway with projection of forces

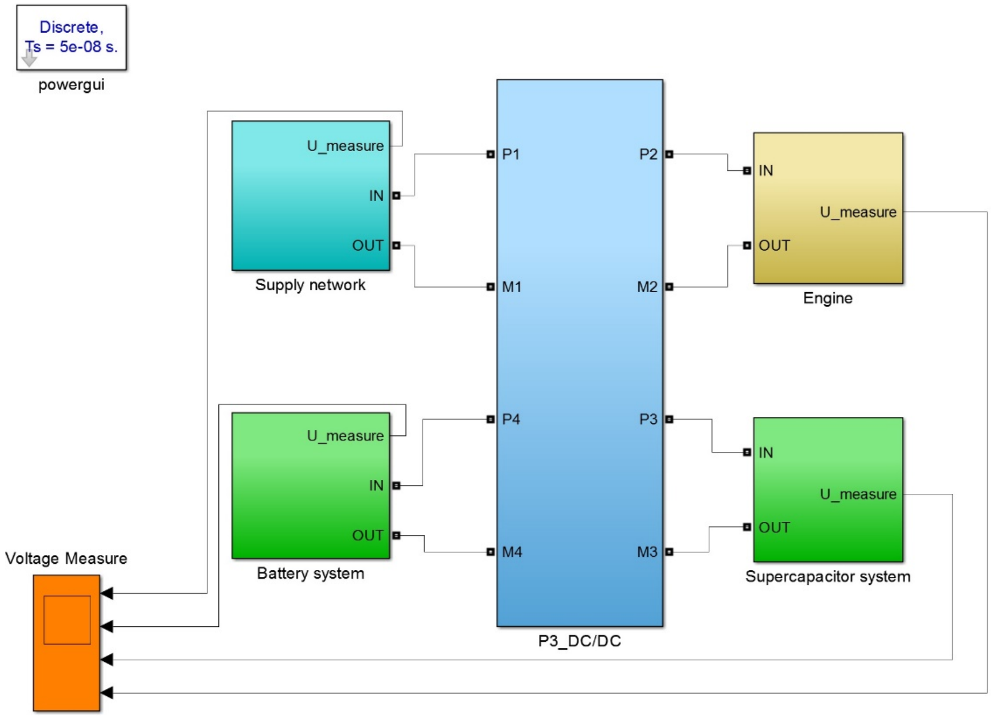
5.3. Model of electric parts of tramway

Electric model contains for basic parts. It is supply network, DC-engines (in this case that is only one engine), supercapacitor store system and battery store system. These part are represented by subsystems as we can see on Picture 27.

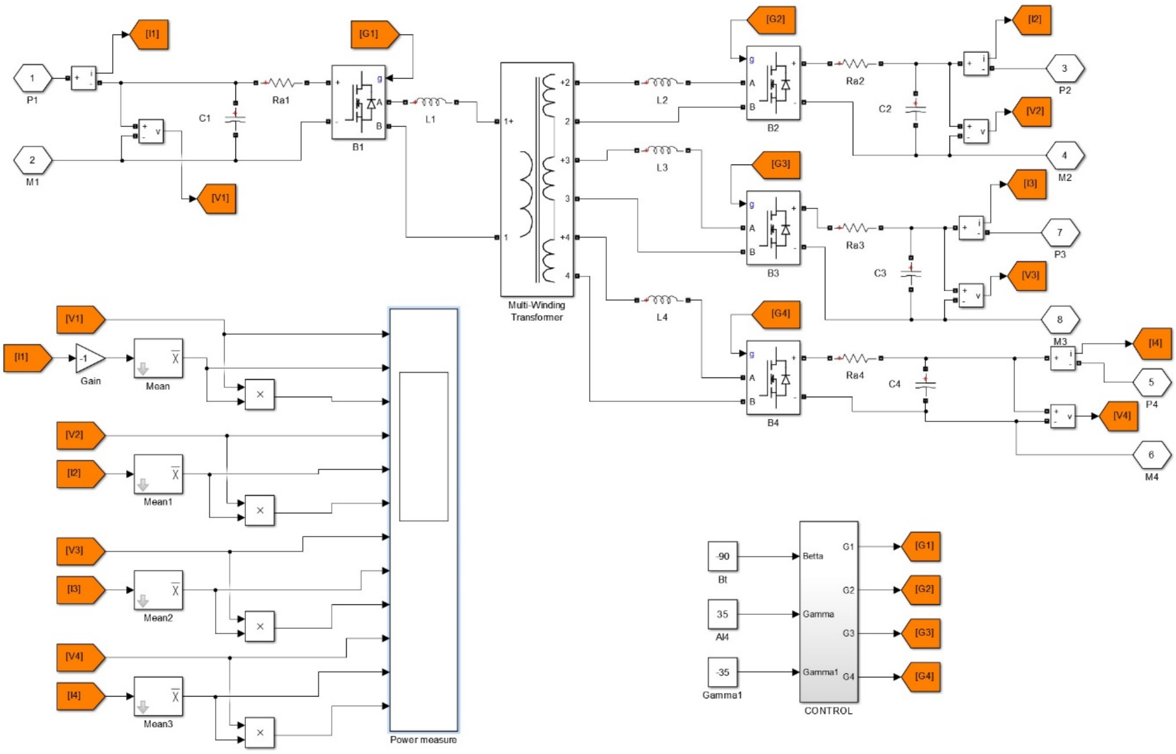
All these parts cooperate together through 4 winding transformed that is a heart of energy change. Every part of these four have its own control device that is managed with changing of angle of signal. According to this, all the energy transfers between the supply system and engine, or engine and store systems is controlled by control device that consist hour signal and few logic operations. At the beginning we mix the hour signal with angle value in radians. Then is used function reminder after division and after it we create a 1-D interpolation of data. Next step is to downgrade the value by 1 and finally we compare, if the value is higher than zero or not and convert them into double type to have more precise value. In the output is the signal multiplexed to output package and sent to specific control device.

More precise scheme and detail of connections into *P3_DC/DC* we can see on the Picture 28. After all procedures are the values measured and from these measured values of voltage and current is calculated as well power and all these values could be depicted into graphs.

Unlike the mechanic model, this one is more specified and use only very simple mechanic model. This model do not prove the real model that can prove all the ride and it is only like an example. However it is possible to add to this model all the mechanic stuff and improve this model to more realistic one, calculations will be really long and except of engine inside features are all the other features the same.



Picture 27- Model of electric system



Picture 28 - Simulink model of converter

6. Economic part

A number of companies produce supercapacitor technologies. Some of the leading companies are Maxwell Technologies (US), NESSCAP (South Korea) or Panasonic – Matsushita Electric Industrial Co., Ltd. (Japan). Between these manufacturers are differences not only in technologies but also in price. Main competitive factors in this industry are price, reliability, performance, durability and operational lifetime. In this topic I would like to prepare SWOT analysis of hybrid APS system, cost analysis and check if this technology could be reliable according to life-time of supercapacitors, batteries and convertors. This reliability is checked the best way by “Net present value”, which consider as well question of time and is more suitable than only use of payback period method, which is too basic and not showing so exact results.

6.1. SWOT analysis

This is an analysis for strengths, weaknesses, opportunities and threats. In common way, we can say, that this method is used for structured planning, which evaluates these four elements of business project. It specifying the objective of the business venture or project and identifying the internal and external factors, which are favourable or unfavourable to reach the target. We can describe these four elements as:

- Strengths: Characterize business plan in way of giving an advantage over others to it
- Weaknesses: characterize places of project, which are in disadvantage to others
- Opportunities: characterize elements of project which could develop project or can change in future advantages

- Threats: characterize elements, which could develop into trouble or cause some failures in project future

Value of information received from SWOT analysis is high, because we can use this information in later planning to achieve objects and avoid difficulties or trouble. Firstly, we can use this data to realize whether our goal is able to achieve. If this goal is not attainable, we must select a different objective and repeat the process. In the Table 3. we can see SWOT analysis for project of use of alternative power source (accumulator batteries + supercapacitor) in vehicle of city railway transport. As output we can see, that most of abilities are mentioned in part of strengths and we can interpret this result as one of a pros for realisation of this project. On the other hand we have to take care about harmful features such as acquisition costs or additive purchasing costs, such as converter which is need to convert current flowing into and out of APS system. Our future threats are reliability and potential costs of renewing of technology. Although lifetime of system is declared about 15 years, we still have to consider if this technology will be mass produced in the future or even there is possibility to leave.

	HELPFUL	**HARMFUL**
INTERNAL (or PRESENT)	**STRENGTHS** fast charge and discharge rate cycle life close to 1 mil. no maintenance decrease of vehicle operating costs	**WEAKNESSES** acquisition costs long payback time need of converter
EXTERNAL (or FUTURE)	**OPPORTUNITIES** mixture of batteries and SC for service in distance without supply network developing technology	**THREATS** reliability Initial costs of new cells

Table 6 - SWOT analysis of using APS in tramway

6.2. Cost analysis

6.2.1. Capital investment costs

For appropriate economic analysis we need to know the whole amount we need to use for purchasing the APS system, how much can the hybrid APS system save that we can later find the time of payback period.

6.2.1.1. Estimated investment costs for APS system for one tramway

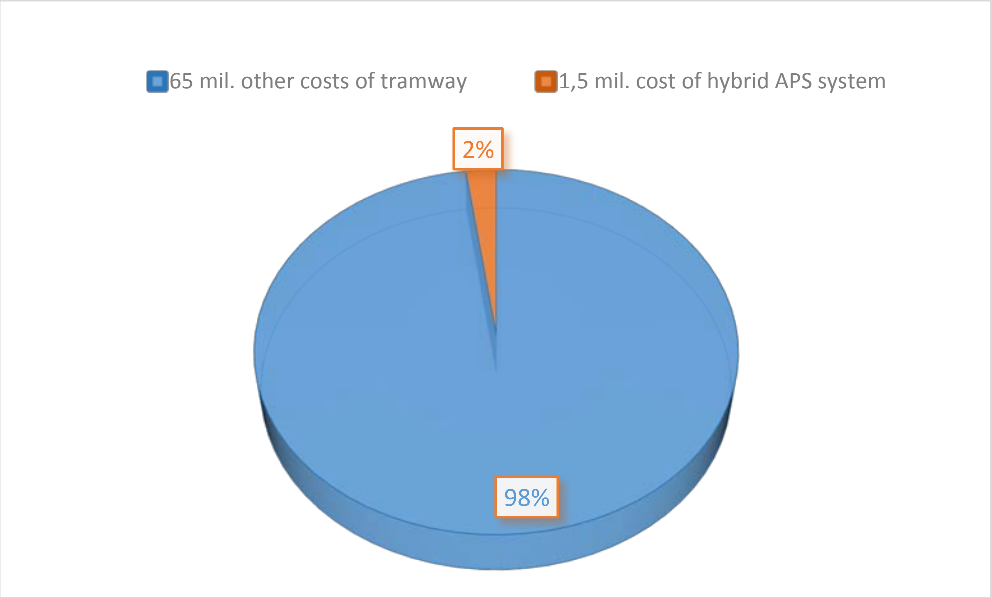
Pricing of investment costs for this system is tougher in more ways. As a first point is necessary to appraise estimated amount of money used to purchase the system. As the second step, we need to count as well human labour as gross wage for installation of the system. In addiction is very important to add calculation of transport costs and potentially custom duties and taxes. Value of 160 CZK/ hour for human labour is chosen by fact of real gross wage of installation workers in Czech Republic. Price of supercapacitors and batteries was chosen from internet shop, although the price for these elements cloud be lower according to some bulk discounts or agreements between companies. The hardest part was to set the price of supercapacitor, which is estimated according to prices of convertors designed for 45kW of power and upraised about 30% which seem to me like obvious price for converter which could work with 3 different types of supply feature such as supply network, supercapacitor system and accumulator batteries. In case of human work was estimated as well time and labour demand, due to fact, that these works are still done in manufactures and this is only my estimation of time which is need to reconstruct tram for hybrid system. Time is set for 2 days because this kind of systems is usually supplied as building blocks only to stick and plug.

NAME OF ITEM	QUANTITY [PCS]	PRICE/PIECE [CZK]	TOTAL PRICE [CZK]
SUPERCAPACITORS BCAP3000	1400	120	168000
BATTERIES LT-LFP300	84	9035,511	758982,92
CONVERTER	4	360 000	280000
GROSS WAGE	4 workers/ 2 days	160/hour	10240
		Total without taxes	1217222,9
		Total + 21% tax	1472839,7

Table 7 - Pricing of system required items

6.2.1.2. Proportional analysis of new tram costs in comparison to costs of APS system

If we consider new type of Skoda Transportation tramway 15T, which price is about 65 mil. CZK, is the total price for this system around 3 mil. CZK only small part of whole tramway price. In the next topics will be considered if this investment could be useful and how long it will take to return money from the investment. As we can see in the Graph 22, this investment could be only about 4% of total investment costs of the whole new tram.

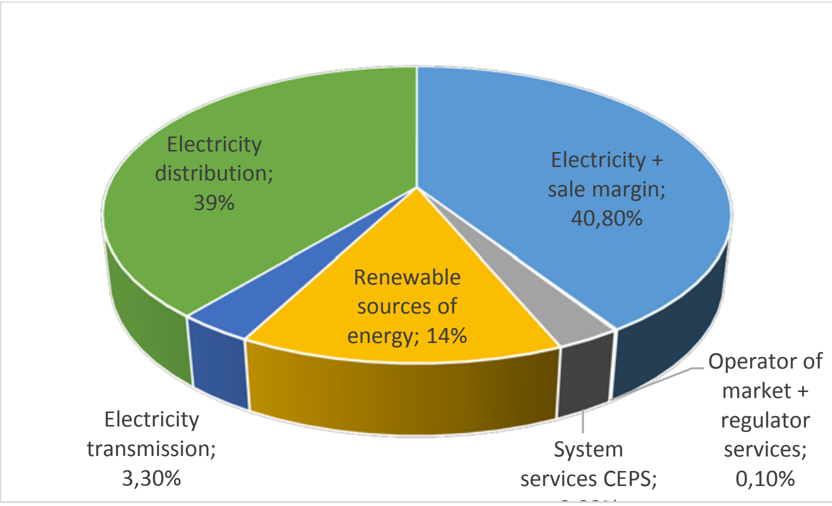


Graph 22 - Amount of costs comparison

6.2.2. Energy consumption

6.2.2.1. Costs of electricity in Czech Republic

System of electricity pricing model for consumers is divided into three different parts. That is electricity for household consumers, electricity for small and medium companies and electricity for whole-sale. According to topic of this work the only suitable pricing model is for whole-sale consumers. As we can see on the Graph 22 price for whole-sale consumers is divided into 6 parts. Additional part is as well taxes. To reach the total energy savings we need to differ these parts of costs for electricity.



Graph 23 - Proportional graph of electricity price in Czech Republic for whole-sale consumers

In Czech Republic, electricity has non regulated price and this price depends on actual stock market price. On the other hand transport of electricity is regulated by state Energetic regulation agency (ERU) and these prices are regulated every year in November and are valid for one year.

Pricing model for whole-sale companies is based on reserved capacity as we can see in Table 7. Whole-sale companies can choose from two different models. It´s annual reserved capacity and month reserved capacity in megawatts. There is difference between this two pricing models by price for one megawatt which is caused by difference in energy demand. DPP as whole-sale HV consumer have a contract based on annual reserved capacity based on calculations. In future years there is a prediction that company will set up the energetic dispatcher centre, where will be evaluated all the data from network for better prediction and savings on energy.

Type of service	Price [CZK]
Annual reserved capacity [CZK/MW]	170 116,00
Month reserved capacity [CZK/MW]	188 237,00
Overrun price above reserved capacity [CZK/MW]	980 464,00
Overrun price above reserved power [CZK/MW]	752 948,00
Unrequired supply of reactive power [CZK/MVArh]	440
RES and Combined manufacture of energy and heat [CZK/MW]	495
Price for Operator of market [CZK/month]	6,58
Price for system services [CZK/MWh]	99,71
Price for network use [CZK/MWh]	44,12

Table 8 - Regulated prices for energy transport in 2016 valid for HV, PRE sphere of distribution

Because pricing model is based on predictions of energy consumption and power capacity we can see in the table that charges for power overrun of this limit is 3 or 4 times higher for one MW than normal price for predicted MW of power.

As well as charges for overrun is charged as well the power that was not used. So the system predictions should be exact.

6.2.2.2. Electricity spends on tramway service

Annual DPP consumption of energy by is about 370 GWh. This total energy is divided into three divisions:

- Division metro – 225 GWh
- Division tramways – 131 GWh
- Other consumption – 14 GWh[12]

For topic of this diploma thesis is the only important division tramway division with total energy consumption 131 GWh of energy.

For this amount of energy DPP paid annually about 526 mil. CZK. (This info is used from official news release of DPP) If we take into account the easiest possibility we can reach the price 1,4054 CZK/kWh. This price is final with taxes, all prices for services of regulation and transport. That means on tramway service is used annually about 184,107 mil CZK.

6.2.3. Energy demands and savings

According to Table 3, where we can see all the energies that we use for tram No.1 ride, we can calculate total amount of energy that is necessary for ride. It is around 35kWh of energy that is needed for the ride. Because technology is built for using all the saved energy during brake process in acceleration, we have to check every part of our track, from one stop to another and see what part of energy we use from supply network, which part we can use from alternative power source system or even if we have saved enough amount of energy in APS system and we don´t need to power the tram from supply network (S_N) as it is mentioned in Table 9.

Ep (Wh)	Em (Wh)	Rest of energy in APS (Wh)	Percentage used APS capacity	Percentage used S_N capacity	Total Energy used APS [Wh]	Total Energy used S_N [Wh]
-1629,39	891,407	891,41	0,00%	100,00%	0,00	1629,39
-910,598	1076,76	1076,76	97,89%	2,11%	891,41	19,19
-784,262	2106,84	1919,47	72,84%	0,00%	784,26	0,00
-649,986	2649,46	3135,16	33,86%	0,00%	649,99	0,00
-617,639	2473,16	3992,54	19,70%	0,00%	617,64	0,00
-636,499	1524,28	3904,26	15,94%	0,00%	636,50	0,00
-653,834	1856,7	4085,70	16,74%	0,00%	653,83	0,00
-684,243	1598,78	4000,19	16,74%	0,00%	684,24	0,00
-710,617	1997,97	4230,04	17,77%	0,00%	710,62	0,00
-752,94	1652,88	4103,98	17,80%	0,00%	752,94	0,00
-786,012	1101,8	3535,82	19,15%	0,00%	786,01	0,00
-797,564	1187,87	3140,90	22,56%	0,00%	797,56	0,00
-815,901	1065,2	2712,16	25,98%	0,00%	815,90	0,00
-829,503	1122,87	2404,42	30,59%	0,00%	829,50	0,00
-857,042	1008,3	2044,53	35,64%	0,00%	857,04	0,00
-1102,04	888,596	1464,87	53,90%	0,00%	1102,04	0,00
-1103,72	849,204	968,29	75,35%	0,00%	1103,72	0,00
-2168,43	730,003	730,00	44,65%	55,35%	968,29	1200,14
-2433,63	630,016	630,02	29,99%	70,003%	730,02	1703,61
-4067,65	509,614	509,61	15,49%	84,51%	630,00	3437,65
-4803,02	479,654	479,65	10,61%	89,39%	509,60	4293,42
-1982,71	513,826	513,83	24,19%	75,81%	479,66	1503,06
-2390,88	626,077	626,08	29,49%	70,51%	705,09	1685,78
-1567,96	771,612	771,61	39,93%	60,07%	626,07	941,89
-1114,28	1132,6	1132,6	69,25%	30,75%	771,62	342,66
-680,582	2880,82	2666,27	60,09%	0,00%	408,96	0,00

Table 9 - Total energy use on TRAM No.1 line in direction Sidliste Petriny - Spojovaci

Values that could be saved into APS system in the table are set to 80% of the value according to losses in converter, supercapacitors and batteries. Percentage values of APS system are showing percent use of capacity of the APS system that is actually necessary for energy demand. Percent values of supply network (S_N) we can interpret as energy need to fulfil demand of energy that is not able add APS system. For example if the energy demand is 1000Wh and we have saved 200Wh in APS system other 75% of energy we add from supply network.

On the other hand if the energy demand is for example 600Wh and we have saved 1200Wh, we use only 50% of saved energy from APS and 0% from supply network, because we don´t need additional energy.

Conformably to the Table 9 we can see and calculate total energy spends and total energy savings. For this calculation we use equations.

$$\sum_{1}^{27} E_p = 1629.39 + 910.598 + \cdots + 680{,}582 = 35\ 530.9\ Wh$$

$$\sum_{1}^{27} Total\ energy\ used\ APS = 0.00 + 891.41 + \cdots + 408.96$$
$$= 18\ 502.51\ Wh$$

$$\sum_{1}^{27} Total\ energy\ used\ S_N = 1629.39 + 19.19 + \cdots + 0.00 = 16756.79\ Wh$$

From the economic point of view we can see, that more than 50% of energy demand we can supply from hybrid APS system consist supercapacitors and batteries. It means that from starting point on Sidliste Petriny tram stop to end point Spojovaci tram stop, we are able to save about 50% of energy costs.

6.3. Reliability of investment

Best way to check reliability of any changes on existing system is to check value of cash flow in future years according to consideration of time value of money. For this purpose it is obvious to use calculation of Net present Value.[14]

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} - Initial\ investment$$

Where the CF_t is cash flow of t^{th} year and r is rate of return. This value could give us exact value of cash flow due to every year. For our research is important to know the first year, when value of NPV will be positive. It is due to initial investment which is in most cases much bigger than year cash flow.

For this case are prepared 4 different cases according to different conditions.

- Variant 1 – 1.4 CZK/kWh, 53% of demand supplied with APS system, 10 rounds a day, r=5%
- Variant 2 – 1.4 CZK/kWh, 70% of demand supplied with APS system, 10 rounds a day, r=5%
- Variant 3 – 2 CZK/kWh, 53% of demand supplied with APS system, 10 rounds a day, r=5%
- Variant 4 – 3 CZK/kWh, 53% of demand supplied with APS system, 10 rounds a day, r=5%

For all of these variants is calculated cash flow for every year until 15th year. It is due to fact, that life-time of hybrid system based on supercapacitors and batteries is not more than 15 years. Due to outcomes of this calculations we can see if this technology could be suitable for use in real life or this case study shows that this technology is too expensive for realisation.

Variant 1 is a realisation of real-time price for 1 kWh of energy with under-designed supply demand with maximal value of 10 rounds a day with real-time rate of return. Although Variant 2 is different by supply demand, which is about 70% which is maximally reachable on this track, this value is different in comparison to first variant because in case of first variant we use coefficient of 80% of saved energy. In real life we can reach only about 3-5% of loses. Variant 3 and Variant 4 are different in price for 1 kWh of energy.

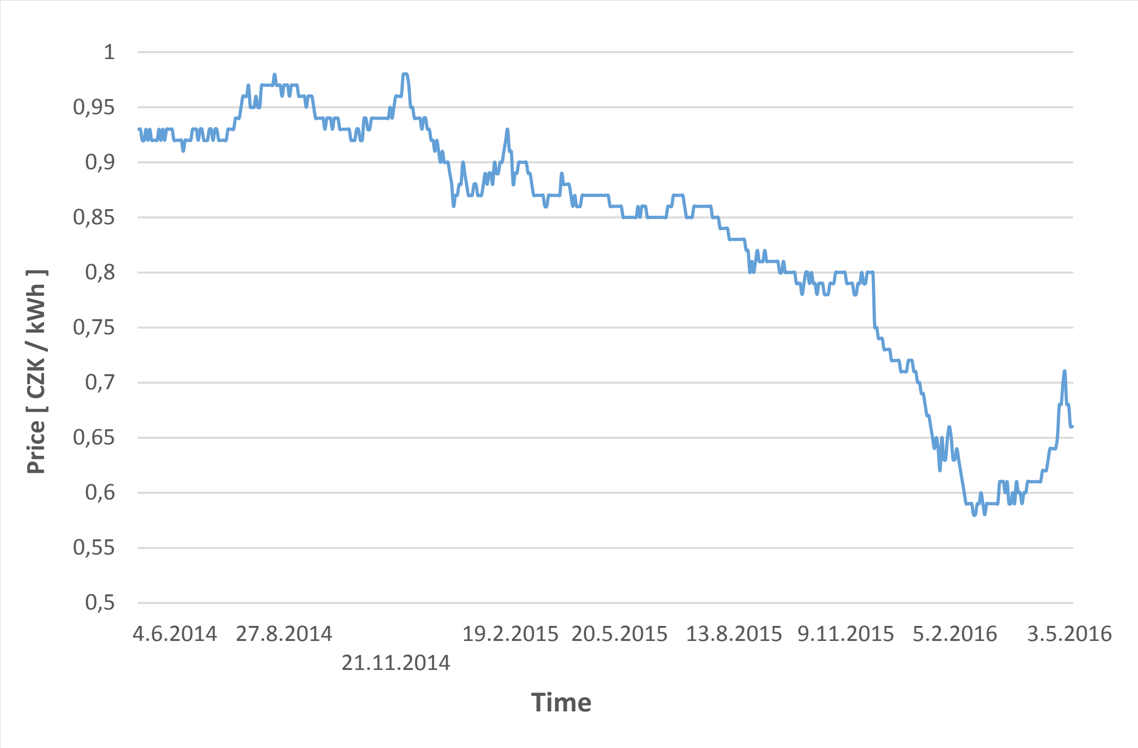
YEARS	VARIANT 1	VARIANT 2	VARIANT 3	VARIANT 4
1	-1472839,738	-1472839,738	-1472839,738	-1472839,738
1	-1292753,605	-1220719,151	-1215573,833	-1086940,881
2	-1121243,002	-980604,3069	-970558,6859	-719418,1598
3	-957899,5699	-751923,5027	-737210,9265	-369396,5207
4	-802334,397	-534132,2606	-514974,9651	-36042,57865
5	-654177,0894	-326712,03	-303321,6686	**281437,3661**
6	-513074,8917	-129168,9532	-101747,1005	583799,2183
7	-378691,8463	**58967,31037**	**90228,6787**	871762,8871
8	-250707,9935	238144,7043	273062,7541	1146014
9	-128818,61	408789,8413	447190,4449	1407205,536
10	-12733,48272	571309,0194	613026,341	1655959,381
11	**97823,78132**	726089,1891	770965,2896	1892867,803
12	203116,4137	873498,8744	921383,3359	2118494,873
13	303395,1113	1013889,051	1064638,618	2333377,796
14	398898,6327	1147593,981	1201072,22	2538028,199
15	489854,3674	1274932,01	1331008,984	2732933,345

Table 10 - Table of Net Present Value values of all variants

According to Table 10, best result we got in the variant with highest possible 1 kWh price of 3 CZK/kWh and the lowest result we got in the case with real-time 1 kWh price of 1.4 CZK/kWh with 53% of demand supplied by hybrid APS system.

6.4. Economic conclusion

Results obtained from economic research of reliability shows that this technology, in case of life-time 15 years, is too expensive for realisation in present, due to low prices of electric energy and quite high initial investment costs. This is valid for case of reconstruction of older vehicle. In case of purchasing a new one, is possible to prove really easily that due to costs which are higher only about 2% and this initial cost is not so high to have bigger savings and higher cash flow. If we are considering the second variant the reliability is better and we can get positive NPV value in 7th year. Especially when we look on the price in 15th year, we can see that this price of "saved" money is enough to purchase a brand-new batteries and supercapacitors for the next service of system. This could cost about 90k CZK so still there is some money saved. For results of calculations from variant 3 and variant 4 we can look like for one case. Because of higher price for 1 kWh of energy supplied from supply network the result is better and more suitable for city tramline operator.



Graph 24 - Trend of energy prices in Czech Republic (between dates 04.05.2014-03.05.2016)

However in these days are these variants unrealistic, due to Graph 24, is it clear that last year and a half is energy price decreasing due to many factors such as oil or coal prices. However, we are looking for the highest values about 1 CZK/kWh is it important to mention that this price according to part 6.2.2.1. is only 40.8%. This means that potentially in the future, if the energy market will grow and energy will be more expensive, could this price reach up to 3 CZK for 1 kWh of energy and in that case is the payback period only 5 years and after 15 years of service could this hybrid system save higher amount of energy that could mean up to savings of 2 million CZK.

7. Social responsibility

7.1. Law rules, regulations and acts of parliament concerned to noise from public transport services

Obligatory rules concerning the noise from tramway service is legislative act No. 258/2000 Sb. This legislative act contains care about communal health according to service of transport. It assign that company that service the communal transport services have to take care about level of noise from transport services due to obligatory CSN regulations. Another document, act of parliament 205 from date 27.11.2000 about healthcare against averse effects of noise and vibrations published in legislative act 146/2000 set hygienic limits of noise emissions and vibrations that could not be exceeded and set possibilities and norms for noise measurements according to regulation CSN ISO 3095 - Acoustics.[13]

7.2. Effects of noise from tramway service according to quality of life

Traffic noise is time variable noise with variable spectrum, but downgrading tendencies to higher frequencies. Intensity of traffic noise could be affected by:

- Sped of vehicle
- Technical conditions of vehicle and track
- Number of vehicles riding in interval we check
- Distance of noise source to the measure place

To better understanding regulations and law acts for level of noise other things that can affect the amount of noise is:

- Surface of terrain
- Natural and artificial barriers

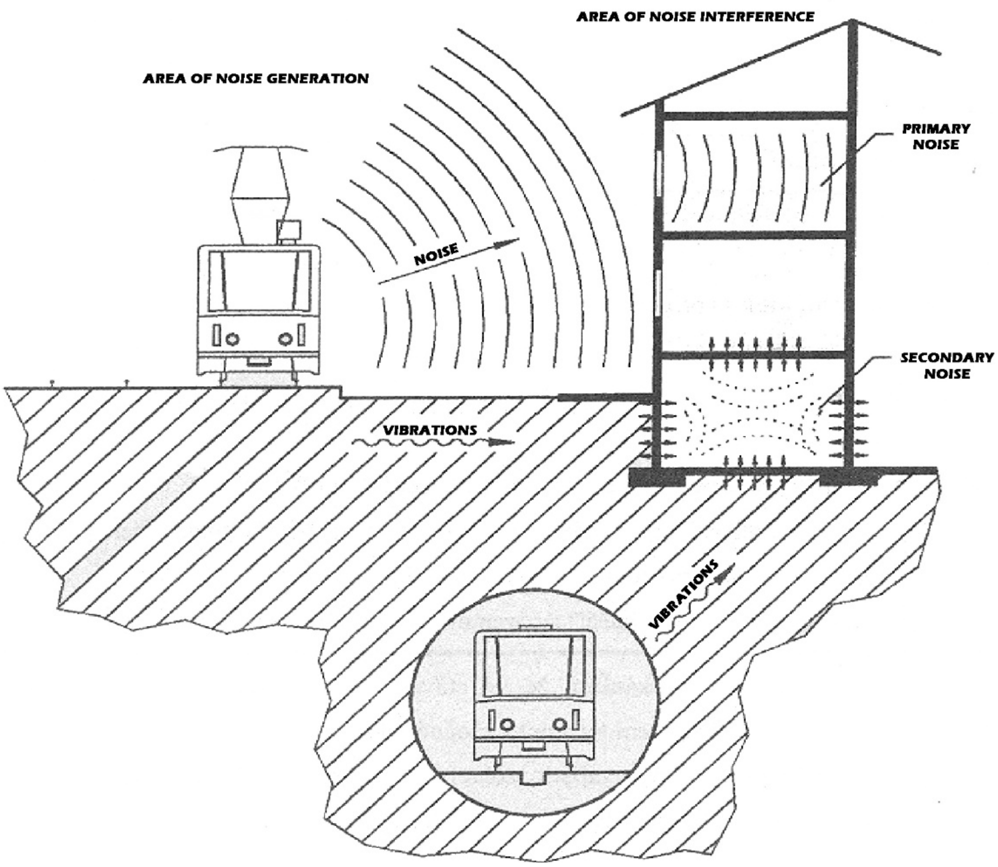
- Climatic conditions (rain, snow, wind)
- Character of noise source.

Traffic noise contains many different noise parts. Sources of these noise parts are all of the rotating components. Because the vehicle is moving on the ground, all the oscillations are moving through the ground and could affect building statics and life quality of people living in building near to tramway track. In means that as noise source is not only vehicle and track as noise emitted into air, but as well in for of vibrations can affect on buildings around, which can oscillate, or noise in for of vibrations can oscillate area and create secondary noise as it is illustrated on Picture 29.

Rail vehicle noise or tramway transport belongs to transport that could make a lot of different types of noise but as well many of them could be edited by different technologies. Noise created from railway vehicles is mostly created from rolling noise (wheel x rail), noise from engines and traction systems (compressors, cooling, ventilation), noise from oscillation of vehicle body, aerodynamic noise and current collectors noise, and other transport noises such as noise from brakes, acoustic system in tramway, warning signals etc.

In case of rolling noise we could calculate very easy by equation below, where $L_2 - L_1$ is change of noise level during change of speed $v_2 - v_1$and c_v is a constant for limit speeds. These limit speeds are: $c_v = 10$ for speed until 60 kmh^{-1}, other values for this constant are unimportant for this work, due to fact, that tramway we use cannot ride more than 60 kmh^{-1}.

$$L_2 - L_1 = c_v * log\left(\frac{v_2}{v_1}\right)$$



Picture 29 - Illustration of noise effects on ambient area[15]

This speed limit constant performs which kind of noise is the most important and especially in kind of vehicles with speed until 60 kmh^{-1} is the most common rolling noise. In higher speed until 280 kmh^{-1} is the value of this constant 30 and most important noise is noise from engines and for the speed higher than 280 km/h is the most important noise aerodynamic noise and constant value is 70. Rolling noise is emitted in height maximally 1 meter and noise from engines from 1 until 4 meter high.[15]

Percent content of noise in tramway service in Prague (but this value is common for most parts of the world) is 85% of rolling noise and 15% of noise from engines. Aerodynamic noise, due to small speed, is not included.

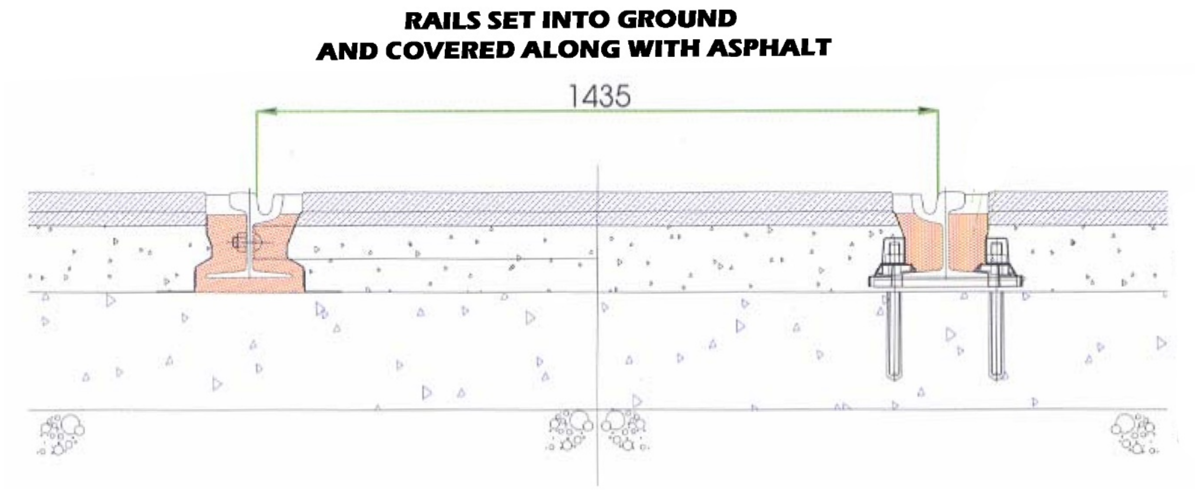
7.3. Solutions to eliminate the noise from tramway service

The solutions are divided into two categories, active and passive. Active solutions to eliminate a noise from tramway service is for example to build a highly used tramway tracks out of historical parts of city or far from areas used for living. Architectonic defence of objects means that objects are built in consideration to local community roads and tramway tracks. Objects built in parallel way according to road or other type of transport area are hit by the noise only from one side. It means the other side is in quite part. This type of architectonic saving against of noise is mostly used in Prague Old city part and New city part, where these building are saved against the noise by the arrangement into square blocks of houses. That means the noise affect only front part and the backyard parts are without any noise from the street. This is called acoustic shadowing.

Organisation of solutions against noise could as well contain solutions from transport side. It could be limitation of speed (at night-time), qualifying of public transport and better traffic control.

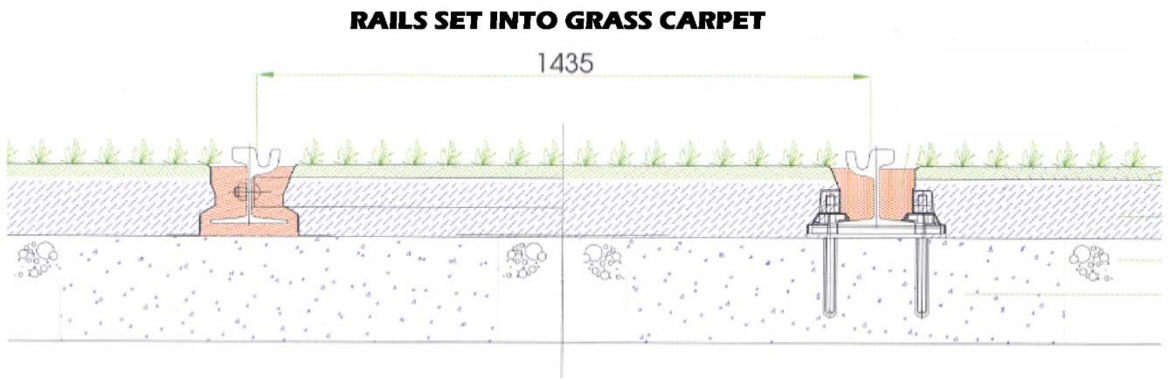
Technical issues to silence the noise are done on vehicle as well. This should contain absorbers of energy from tramway track, spring loading, use of covering for the parts of boogies and good technical conditions of tramway.

The most important for elimination of noise are good conditions of railway track. It is true that even exact type of rail can influence amount of noise from tramway service. One of the possibilities is to use monolithic concrete boards, where are installed rails and use special anti-vibrating underlays. To stabilise the track width are the tracks stacked together with iron roots. This technology is used on many different track parts and mostly for multifunctional use is the upper cover asphalt, that busses can service the stops as well.



Picture 30 - Rails set into asphalt

Another possibility is to eliminate a noise from tramway service is use of grass carpets, where is used effect of noise absorption through the grass and ground . Rails are put on the gravel, where is used geotextile and above it is used earth and grass. As we can see on the Picture 31, the grass is set few centimetres lower than rails which can absorb the noises and vibrations in better way.



Picture 31 - Rails set into grass carpet

To summarise, there are many ways how to eliminate the noise from tramway service, the most important is to use as much as possible solutions for tramway track, because the good conditions of track can affect more than 50% of noise. Other possibilities is to manage some covering and better carriage body designing to eliminate the noise leaving the tramway.

Epilogue

Main aim of this work was to prepare a case study of possible use of alternative power sources in Prague tramway lines. Research began with choose of the most appropriate tramway line, that can prove the best possible numeric results. For this purpose was chosen the line number 1. This tramway line have the biggest altitude difference 82 metres. Profile of this tramway track is from the beginning downgrading until the approximate middle part. After then the track starts to step into hill on Krejcarek tram stop and then on Ohrada and Strazni. After this tramway stop has the tramway track again downgrading character. To explain the better results for this track has author chosen another 2 different tracks from tramway lines No.7 and No.13, to compare altitude difference in comparison to length of this track.

After choosing appropriate track was this track set into Matlab, where it was transformed into approximated function by 5th order. This was done due to fact that is much easier to work next only with function which have the same characteristics as dependence graph of altitude to length of tramway track.

As another important part was to set the speed between tramway stops. There is showed real data in the graph below, but in final decision was used easier solution that we manage between all stops acceleration of $a=1.1ms^{-2}$ until the tramway will reach the speed of 50 kmh^{-1}.

With these data and basic technical data about used tramway we were able to calculate other parameters of drive. From all the forces that accelerate and affect against tramway ride we could calculate power and energy used for tramway work on the track. Final graphs we could see inside of this work. These energies were later used for calculations of number of appropriate source quantity. In our case it was calculations for quantity of used supercapacitors, batteries or both in hybrid system.

As final technical solution was chosen hybrid system based on combination of series-parallel interconnected batteries and supercapacitors that are divided into 8 parts. It is due to fact, that tramway we use for our calculations consists 8 DC-engines so in fact every engine consist one branch of batteries and 2 branches of supercapacitors.

Economic part have a main point of research to prove sustainability of this solution. For the beginning was mentioned SWOT analysis to interpret all the positive and negative features of this solution that can affect our final decision. Main analysis of sustainability is based on calculations of Net present value and interpret this calculations as: “How many years it will take until this solution can start earn money and it eliminate all the initial costs”. Calculations showed, that solution of use of this technology could be valuable in case of new tramway, but couldn´t be valuable in case of older tramway reconstruction. Calculations was done with nowadays energy prices and possible future prices of energy that were set higher. In case of more expensive energy is this solution more valuable as well for the older tramway reconstructions.

Last part was targeted to social responsibility and especially to noise that is made from tramway transport. It was mentioned what kind of noise could exist and how it could affect quality of human life in nearest buildings next to tramway tracks. Last part of this topic could explain some techniques how to minimize these noises and vibrations with some different technologies.

This work reached the targets that were set on the beginning and I as author hope that the work could bring some new positive thoughts or discussions to professionals about future way of tramway transport in Prague and how to improve technical part, economy part, how to reach ecology normative and improve quality of human life around tramway tracks. As future goal is set to design an automatic control system for control of angle for energetic scheme. This topic is huge that is why we didn´t mentioned it in this work.

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