DYNAMIC CHARGING OF ELECTRIC BUSES

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1. INTRODUCTION

Despite the continuous development of electrochemical battery technology and the multitude of electric buses on offer, it is still not possible to exploit electric buses in urban transport on an all-day basis without the necessity of charging them. It is therefore necessary to build point-to-point contact charging stations or induction charging stations at the terminals. This results in substantial financial outlays connected with the construction of charging stations, and the need to extend stopping times at terminals; there are also problems which could arise in situations where bus routes are. The alternative solution is Dynamic Charging System of electric vehicles also known as In Motion Charging (IMC). It is achieved by building an infrastructure that allows for the charging of vehicles while in operation, most often via the use of overhead contact lines.

Dynamic charging is a combination of standard battery bus and trolleybus. This solution allows you to split the advantages of battery buses and trolleybuses. Dynamic charging involves the supply of electricity during the movement. It can be done in a wireless way (linear induction loops) or in a contact manner (traction network). Currently, the most widespread dynamic charging system is the trolleybus traction network. This solution allows to supply energy to an electric vehicle without turn it off from traffic.

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2. CHARGING OF ELECTRIC VEHICLES

The charging of electric vehicles is a broad issue. Multiple classifications can be applied, depending on the choice of criteria. The most important criteria for classification are operational as well as technical aspects. Hence, we can distinguish:

1) division into charging strategies from the operational and motor aspect
2) division into charging methods from a technical implementation point of view.

From the operating and operational point of view, there are four main charging strategies:

1) stationary charging overnight in the depot, low power 30 - 60 kW,
2) stationary charging in the depot together with recharging during the day using medium (100 - 200 kW) or high power (300 - 600 kW) charging stations
3) fast charging only at end stations with high power (300 - 600 kW)
4) dynamic motion loading (In Motion Charging, IMC).

From a technical point of view, charging methods can be divided as follows:

1) charging with a plug-in connector
2) charging in a four-pole system
3) charging in a two-pole system
4) In motion charging (IMC)

Table 2.1. Comparison of charging strategies and charging systems indicating which charging strategy can be implemented by means of which charging systems

	Technical charging method				
Charging strategy		Plug - in	Four - pole system	Two - pole system	Dynamic charging
	Night charging	YES	YES	YES	NO
	Nigth charging with re-charging during day	YES	YES	YES	YES
	Fast charging	NO	YES	YES	YES
	Dynamic charging	NO	NO	NO	YES

It should be noted that some charging strategies overlap with others in regard to technical criteria. Table 2.1 presents a comparison of technical charging methods in terms of

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the ability to handle individual charging strategies. For example, vehicles adapted to the dynamic charging method may also work in a fast charging strategy or, in the case of having a sufficiently large battery, in night charging with recharging. A transport system using a fast charging strategy can be operated by a four-wire, two-wire or dynamic four-wire method.

2.1. Classification of charging strategies from the operational point of view

The process of charging electric buses is a factor in determining the functioning of this means of transport in the public transport system. The charging time of traction batteries varies within a wide range, from several minutes up to several hours. The vehicle's working cycle is highly dependent on this charging time.

Currently available battery technologies allow electric buses to achieve ranges between 150-200 km. Further increases in the coverage area require significant associated increases in battery weight. A range of 150-200 km is insufficient for servicing all-day tasks on public transport lines. It is therefore necessary to recharge the bus's battery within the working shift, which requires the vehicle to be removed from traffic. Therefore, in such an operational regime it is only possible to operate peak transportation routes.

The disadvantage of night charging is the very large capacity of the traction battery, which causes a significant increase in the weight of the vehicle. In addition, it also involves significant costs in replacing the battery at the end of its lifetime. Reducing the capacity of the battery can be achieved by increasing the charging power to 300 - 600 kW, as a result of which it is possible to significantly reduce its capacity - up to 60 - 90 kWh leading to a reduction in the weight and dimensions of the battery. Charging the electric bus, however, requires the vehicle to be out of operation for a period of about 10 - 20 minutes. These periods must be incorporated in the timetable and require an increase in stopping times at the end terminuses or stops. As a result of this, more electric buses are required to operate the route compared to classic buses or trolleybuses. It is also possible to recharge traction batteries during stops along the route. This requires an extension of the stopping time to about one minute, which is possible only in special situations.

Another solution is the dynamic charging of vehicles (IMC). This involves the supply of electricity during movement and can be done in a wireless way (linear induction loops) or in a contact manner (traction network). Currently, the most widespread dynamic charging system is the trolleybus traction network. Work is also underway on the application of this type of power supply for trucks (eHighway project) and public transport vehicles (Electro road).

2.2. Classification of charging methods from the technical point of view

2.2.1. Plug - In charging

Traction batteries, requiring charging, are installed in the buses to provide the power source. The easiest way to charge these batteries is to do so while the bus is at the depot for a stopover at night. This type of charging can be compared to refueling for internal combustion buses. Battery capacity is closely aligned with the range of the vehicle. Increasing the range requires increased battery capacity, which brings with it increased vehicle weight and energy consumption.

It is possible to charge via DC or AC current. Today, available solutions allow for charging with a current of 60 - 100 A, which corresponds to a charging power of up to 60 kW. Plug-in systems with higher power have been tested, even up to 500 kW, but they are not popular. Due to the limited power and troublesome process of manual connection of the vehicle to the power source, the use of this method is in practice limited to night charging mode. Fig. 2.1 shows an example of a plug-in charging system.

Fig. 2.1. An example of a plug-in charging system (Bremen)

2.2.2. Four-pole charging system

In a four-pole system, charging takes place using a DC voltage of 600 - 900 V. The vehicle is connected to the charging station by means of a pantograph collector with 4 connectors (wires - poles):

- positive charging pole,
- negative charging pole,
- protective grounding pole (so-called earthing),
- grounding control pole.

The protective grounding pole is used to provide protection against electric shock in the event of damage to the insulation of the electrical installation. Due to this safety requirement, it is necessary to ensure a reliable connection between the vehicle body and the earthing-grounding pole. This involves the need to control the earthing-grounding connection and, for this purpose, an additional grounding control pole is used. Additonally, a sensor wire may be used to transmit data between the vehicle and the charging station.

The charging station is equipped with a charging converter – the so-called charger. Charging power is usually in the range of 150 - 350 kW, but installations with a capacity of up to 600 kW are used.

Fig. 2.2 presents a schematic diagram of a four-pole charging system, Fig. 2.3 and 2.4 show examples of realizations. The pantograph may be part of the vehicle (figure 2.3) or part of the charging station (figure 2.4).

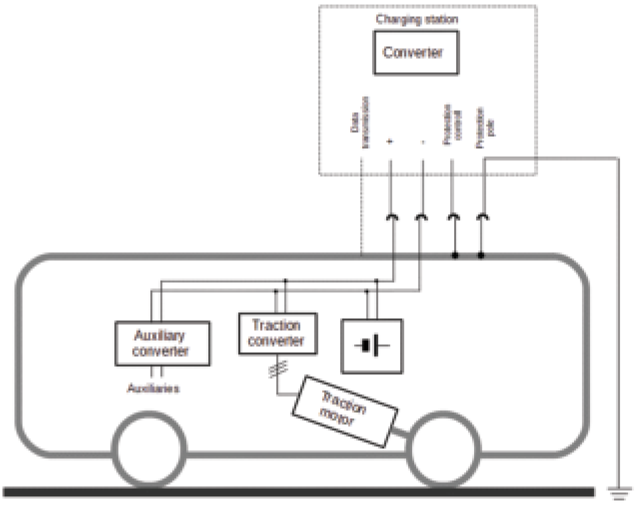

Fig. 2.2. Charging in four pole system

Fig. 2.3. Pantograph of charging system system Shunk (Kraków, Poland)

Fig. 2.4. Pantograph of charging system system Opp Charge (Turku, Helsinki)

2.2.3. Two-pole charging system

In a two-wire system, charging takes place using a DC voltage of 600 - 900 V. The vehicle is connected to the charging station by means of a pantograph collector containing 2 poles (positive and negative) from a short section of the trolleybus system. It is the simplest charging system for electric buses in the case of a previously existing tram or trolleybus overhead contact line. Charging may take place directly from an existing trolleybus infrastructure, whereas for a tram network it will be necessary to build a short section of the trolleybus network.

The basic problem for this charging system is providing protection against electric shock. Standard electric buses have electric installations made with single-stage insulation. In a two-pole supply system, the vehicle body is not grounded. When charging an electric bus, there is a risk of electric shock if insulation is damaged. Therefore, it is not permissible to connect a non-earthed (non-grounded) electric vehicle equipped with a single-stage electrical installation insulation to the electric power supply. Consequently, for a charging method based on a two-pole system, it is necessary to incorporate two-stage insulation for the electrical installation of the vehicle (analogous to trolleybus insulation) or to use a separation converter in the vehicle, as shown schematically in Fig. 2.5. The weight of this converter is between 200 - 600 kg, which significantly increases the weight of the vehicle. Implementation of the converter also involves financial outlays. It is possible to install a separation converter in a stationary form. This solution was used at the electric bus charging station in Prague (Fig. 2.6).

The charging power in a two-pole system is limited by the maximum current of the pantograph collector. Currently used pantographs allow for a current of 200 - 300 A, which corresponds to 150 - 200 kW of charging power.

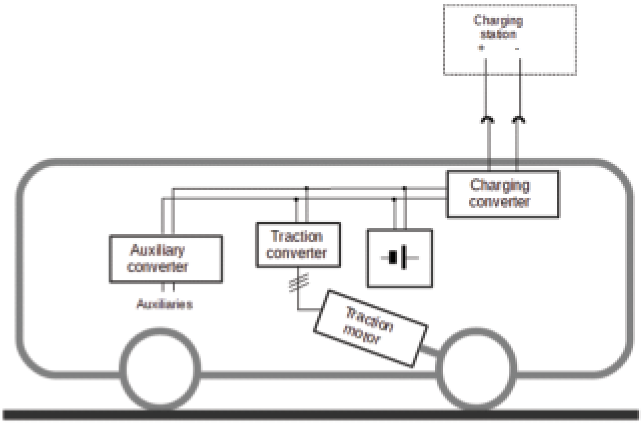

Fig. 2.5. Charging in two pole system

Fig. 2.6. Electric bus charged in two pole system (Praha, Czech Republic)

2.2.4. In Motion Charging (Dynamic charging)

The dynamic charging system is a combination of two-pole charging with trolleybus technology. In the dynamic charging system, part of the route is covered with a trolleybus traction network, which allows for the charging of traction batteries during movement (Fig. 2.7). The vehicles cover the rest of the route, i.e. the part in which there is no contact line, using traction battery power. This allows for the charging of the vehicle without stopping, increasing the flexibility and functionality of the system. In addition, covering a section of the route with a traction network reduces the length of the route to be travelled in battery mode, which in turn allows for a reduction in the capacity of the traction batteries. Tab. 2.2 presents a comparison of charging methods.

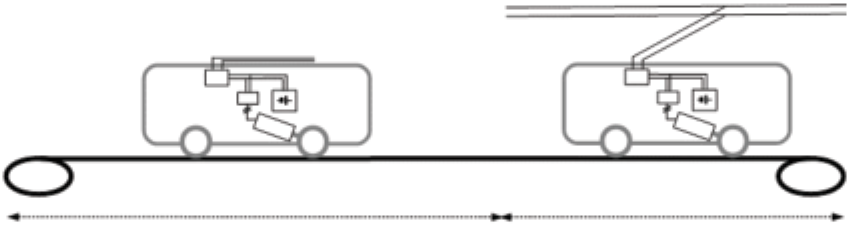

Fig. 2.7. Idea of dynamic charging system (In motion charging)

Table 2.2. Comparison of charging methods

Charging method	Max. charging power	Financial outlays	Flexibility	Advantages	Disadvantages
Plug-In	100 kW	Low	Middle	Low investment costs	Difficult manual connection
Four-pole	600 kW	Middle	Low	The highest charging power	High cost of charging station
Two-pole	200 kW	Low	Low	Easly to integrate with tram or trolleybus supply system	High cost of vehicle
IMC	300 kW while travelling, 80 kW while stopping	High	High	No need to stop vehicles during charging, more flexibility, less battery capacity.	High investment cost

3. THE EXAMPLES OF DYNAMIC CHARGING APPLICATIONS

3.1. Slide–In System in Landskrona

On 27 September 2003 a completely new trolleybus system was opened in Landskrona (Sweden), which received the number 3 in the existing public transport system. It connected the new railway station, the city center and the harbor. The length of line was 3 km and it was originally operated by 3 Solaris Trollino 12 trolleybuses produced in cooperation with the Hungarian GANZ company [10, 27].

The trolleybus line proved to be a very good solution and quickly became the backbone of the city's transport. An increase in passenger traffic led to the decision to purchase a fourth trolleybus, which was put into service in 2010. There were also suggestions to extend the trolleybus transportation system, however the relatively small size of the transport operation on the bus lines meant that it was not profitable to extend the traction network. The solution to this problem was to add an auxiliary drive to the trolleybuses that enabled them to move on sections without a traction catenary [4]. This project was made possible by the SlideIn project.

SlideIn is funded by the EU's LIFE + program. The main partner in the project is the University of Lund. The other partners are: Skånetrafiken, ÅF (Landskron transport operator), Motivationshuset, Volvo Powertrain and E.ON [33]. The budget was estimated at 1.6 million euros, and its implementation time was September 2011-December 2015. The task of the project was to construct a SlideIn electric bus, test it in operation and evaluate the results. Due to geographical localisation and favorable conditions, it was decided to operate the electric bus in nearby Landskrona and to use its trolleybus network for charging.

The vehicle was designed as a standard trolleybus with enlarged traction batteries enabling the vehicle to move on a section without traction. The power source was lithium batteries with a capacity of 54 kWh and a voltage of 450 V. They allowed for a run of 20 km without supply from a catenary. The schematic diagrams for lines 3, 4 and 5 are shown in Fig. 3.1. Trolleybus was designed to operate on bus lines 4 and 5 in the following work regime:

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1) trolleybus service on line 3, charging from trolleybus catenary, trolleybus goes two cycles (Figure 11, red line),

2) operation on bus lines 4 and 5 powered from traction batteries (fig. 3.2, black and orange lines).

During daytime operation, 70% of the total operational distance is powered by traction batteries, with only 30% of the route using the overhead contact line. The operation of the trolleybus has fully confirmed its strengths. Line coverage of only 30% of the length of the traction network enables operation in electric mode. The maximum discharge of the battery has been observed at 40%, which means that there is sufficient storage capacity in case of traffic disruptions.

Fig. 3.1. Trolleybus system in Landskrona, linie 3 - standard trolleybus line, lines 4 and 5 - battery operation [33]

Fig. 3.2. Slide – In trolleybus in Landskrona

Fig. 3.3. Slide – In trolleybus in Landskrona

3.2. Praha

Prague provides an example of the partial transformation of an electric battery bus system with the addition of some trolleybus functionality. The experiences gained at DP Praha (a public transport company in Prague) during the operation of stationary charged electric battery buses provided the impetus to undertake tests with a dynamic vehicle charging system using a trolleybus overhead contact system. It should be noted that, from 1936 to 1972, a trolleybus system functioned in Prague. Numerous plans for its re-opening were prepared in the 1980s and in the early 1990s, however economic and political changes blocked these plans.

Since 2012, Prague has been conducting a trial operation of electric buses of various systems and manufacturers. One of the observed limitations was the impact of traffic congestion, i.e. the reduced amount of bus charging time available at the final stop in cases of delayed arrival. Additionally, articulated vehicles assume the main role in the Prague bus transport system, which significantly limits the market of available electric buses. The biggest concern however, was the difficult vertical profile of many routes. Prague is a city with large variations in elevation and, consequently, many street have extreme slopes. This creates high demands on the parameters of the propulsion system, which also results in an increase in the weight of the battery. One of the ways of solving this problem is with a dynamic charging system for the electric vehicles. The use of various power supply methods was considered, including using vehicles with two pantograph collectors and a bipolar traction network (similar to trams). However, the most well developed, simple and proven solution turned out to be a trolleybus traction network.

On 22 February 2016, the management of DP Praha approved the "E-Bus s dynamickým nabíjením" project, which translates as "E-bus with dynamic charging". This project involved the construction of a test section of "trolley-type line" for charging electric buses while in traffic. The bus route chosen for the test installation, line 140, is characterized by a large difference in the elevation of the area between the Palmovka start stop and the Prosek settlement, with a road gradient of up to 10%.

During the first stage, a trial line of 140 electric buses using the IMC system was proposed on the shortened route from Palmovka to Letňany, with a total length of 5 km. The trolleybus overhead catenary would be built on a steep section of Prosecka Street, a 1 kilometer section between Kundratka and Kelerka stops, which is 20% of the entire length of the test route. After more than a year of technical project design works, all necessary permits were obtained in July 2017 and the construction of the test section began on August 10, 2017. The construction was finalized one and a half months later. The process of official technical approval took place from 11 to 13 October 2017.

The completed route consists of a two-way section of trolleybus overhead contact line. In the "top" direction, that is from the Kundratka stop to the Kelerka stop, it has a length of 993 meters. In the opposite direction it is slightly shorter measuring 613 meters. At both ends of the route, "roofs" have been installed for the semi-automatic connection of the trolleybus collectors. A prefabricated, container tram substation equipped with one rectifier unit is used to supply the power for the route. It was previously used as a temporary power source during the reconstruction of tram traction substations in Prague. The built-up section, approximately

1 km long, is too short to fully charge the traction batteries. For this reason, a short section of the trolleybus traction contact wires was built on the Palmovka final stop with "roofs" for semi-automatic connection, in order to charge the vehicles while they are stopped. It is powered by 750 V from the tramway traction network using a supply station named "Dobudka." Produced by the Czech company Cegelec, "Dobudka" is a container converter station, providing galvanic separation and increasing the voltage value from the tram network.

The SOR TNB 12 Acumario trolleybus is currently undergoing testing (Fig. 3.4 - 3.6). In the first half of 2018 the next vehicle, the Electron 12T trolley bus manufactured by Ekova (Ostrava) and equipped with LTO batteries with a capacity of 47 kWh, is scheduled for testing. Škoda Electric has also nominated a vehicle for testing. Additionally, there are plans to test articulated trolleybuses, but currently a vehicle with appropriate parameters (mainly for auxiliary drive) is not available in the Czech Republic.

Fig. 3.4. Trolleybus SOR TNB 12 goes uphill on Prosecka street in Prague powered from the traction network

Fig. 3.5. The charging station at Palmovka terminius with "Dobudka" converter station

Fig. 3.6. Trolleybus SOR TNB 12 on Letňany terminous in autonomous drive mode

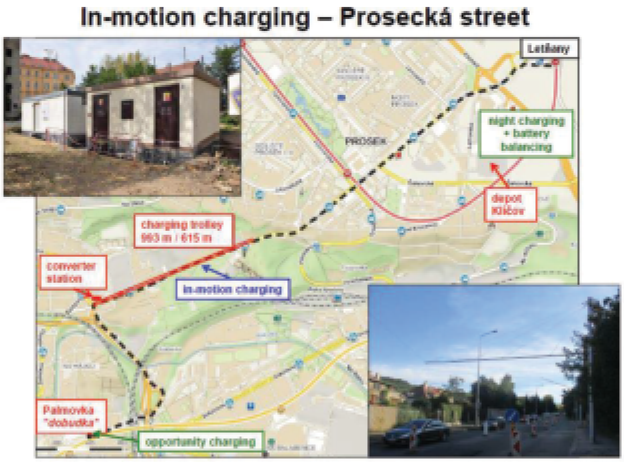

Fig. 3.7. The scheme of test route in Praha [© DP Praha]

3.3. Marrakesh

The BRT system in Marrakesh (Morocco) is an example of an urban transport system that uses dynamic charging through a traction network. The traction network is a reduced one, of a minimum size necessary to efficiently operate the route. Initially, the construction of a tram line was considered as in other Moroccan cities (Casablanca, Rabat). However, due to the high costs, the electrified Bus Rapid Transit system was chosen instead. The BRT line was opened in September 2017 and connects the centre of the city with the western suburbs through Hassan II Avenue, with a total line length of 8 km. The length of the section covered by the catenary is 2,5 km. The line is supplied with 750 V voltage from one traction substation located at the west end of the route. The BRT line operates on separated bus lanes along the entire length of the route (fig. 3.8 - 3.11).

The line is serviced by 10 standard two door Chinese YANGTSE trolleybuses. Each vehicle is equipment with 5 battery packs. Each battery pack has a capacitance of 200 Ah nominal voltage 115,2 V. The total energy capacitance of the batteries is 115,2 kWh. The trolleybus overhead line will be supplied from a 1 MWh photovoltaic plant with an area of 3 ha. The energy generated from the photovoltaic panels will be transferred to the 750 V DC power system with any unused surplus being sold to the power system operator.

The interval of service on the line is 6 min in peak time. In the future there are plans to buy higher capacitance vehicles and extend the route to Medina, the historical centre of Marrakesh. The BRT system in Marrakesh can be seen as an example of a modern electrified transportation system that could potentially be a much cheaper alternative to tram transport with identical transportation capacity.

Fig. 3.8. The western end of the cathenary section of Marrakech's BRT system

Fig. 3.9. The eastern end of the cathenary section of Marrakech's BRT system

Fig. 3.10. Vehicle in off-wire section of Marrakech's BRT system

Fig. 3.11. The scheme of Marrakech's BRT system

4. TECHNICAL ASPECTS OF DYNAMIC CHARGING SYSTEMS

4.1. Trolleybus traction cathenary

Trolleybuses are trackless vehicles, and consequently, the trolleybus traction network is both the supply and return network. It consists of two wires parallel to each other, suspended as standard at a height of 5.5 m above the level of road. Usually, the right-hand wire (external) is the lower-potential (minus) wire, and the left (internal) wire is the higher-potential (plus) wire (Fig. 4.1). However there are exceptions to this rule and trolleybuses must therefore be adapted to work with both polarities of the traction network. Both poles of the overhead contact line have double insulation.

As in the case of railway or tram traction, the trolleybus contact network is divided into supply sections. The overhead contact wire paths for both directions of movement are permanently connected to each other by means of compensatory connections, spaced every 300 - 500 meters. An exemplary diagram of the supply section is shown in Figure 4.1.

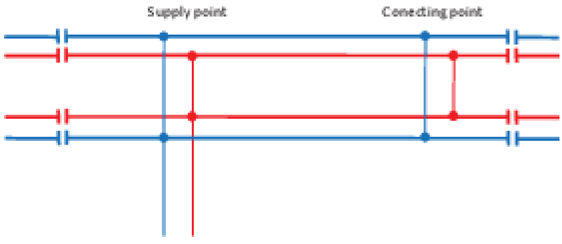

Fig. 4.1. An exemplary diagram of the supply section

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Fig. 4.2. Trolleybus contact line, Landskrona, Sweeden

Fig. 4.3. Trolleybus contact line, Plzen, Czech Republic

In situations of high trolleybus traffic intensity, a significant electric load on the traction network may cause excessive voltage drops. For this reason, additional electrical reinforcement of the overhead contact line may be used to reduce overall electric resistance. One of the means of achieving this is the use of additional DC supply cables. In this scenario the traction network section is powered by several cables (fig. 4.4). Another solution is to use additional overhead wires (fig. 4.5).

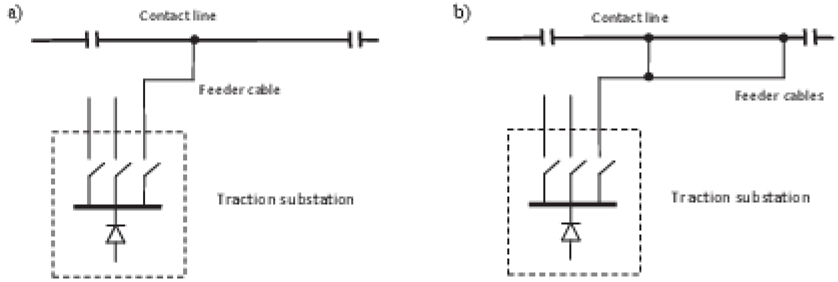

Fig. 4.4. Standard supply section (a) and section supplied by two cables (b) in term of reducing voltage drops

Fig. 4.5. Trolleybus contact line with additional overhead wires which reduces the overall resistance (Budapest, Hungary)

An effective and proven solution is the joint use of transportation paths by trams and trolleybuses. This makes it possible to use the existing tramway track for other public transport vehicles and to limit the impact of traffic congestion (fig 4.6-4.7).

Fig. 4.6. Common transportation stop for tram and trolleybuses, Szeged, Hungary

Fig. 4.7. Common transportation stop for tram and trolleybuses, special design of trolleybus overhead cathenary is visible. Szeged, Hungary

In the case of parallel operation of trams and trolleybuses, it may be necessary to cater for situations where the traction networks of the two transport systems cross. There are currently many solutions for such crossings (fig. 4.8, 4.9).

Fig. 4.8. High speed crossing of the tram and trolleybus overhead line, Ostrava, Czech Republic

Fig. 4.9. High speed crossing of the tram and trolleybus overhead line. Szeged, Hungary

In the case of routes operated by dynamic charged vehicles there is possible to charge vehicles on of - wire section. It can be realized by charging station adapted for trolleybus current collectors (fig. 4.10).

Fig. 4.10. Station for stationary charging of trolleybuses, Cagliari, Italy

4.2. Traction substations

Traction substations convert the energy of the high voltage alternating current received from the power grid into a direct current, supplying overhead wires. Substations can be supplied with energy from 10 kV to 35 kV.

The traction substation consists of three main parts:

- High Voltage switchgear,
- Rectifier units,
- DC switchgear.

In the high voltage switchgear, the incoming energy from the power lines is divided into individual devices located in the substation, i.e. the rectifier unit transformers and a transformer dedicated to the auxiliary needs of the substation – e.g. lighting, heating and control systems. Additionally, the HV segment incorporates meters measuring electricity usage to allow for settlements with the electricity supplier. Due to the high level of reliability required of the power supply, it is recommended to use power from two independent power lines. Currently, the high voltage sections of traction substations do not differ from analogous devices in industrial and energy power facilities.

High voltage energy is converted into DC energy in the rectifier units. They consist of a transformer, which reduces voltage, and a rectifier. There is the option to use rectifier units equipped with additional inverters to allow for the recovery of regenerative braking energy to the power grid. Traction substations may be equipped with one or more rectifier units. Installing at least two rectifier units in a substation increases its reliability.

Converted DC energy is divided into supply sections in the DC switchgear. The key components of the DC segment are rapid circuit breakers, which provide overcurrent protection for the power supply and traction network. The current trigger settings have values between 500 - 3000 A. Due to the high load currents, the random nature of the traction load and safety requirements, important elements of a permanent-current switchgear are the protection relay systems. Elements of the traction substation are shown on fig. 4.11.

Due to the two overhead wires of the traction network, the main element distinguishing a trolleybus substation from a tram or light rail substation is the presence of a minus wire disconnector. It is used to completely cut off the supply of the overhead catenary (for most solutions, one pole circuit breakers are used - in the case of a short circuit in the overhead catenary, the circuit breaker automatically switches off the positive cable only).

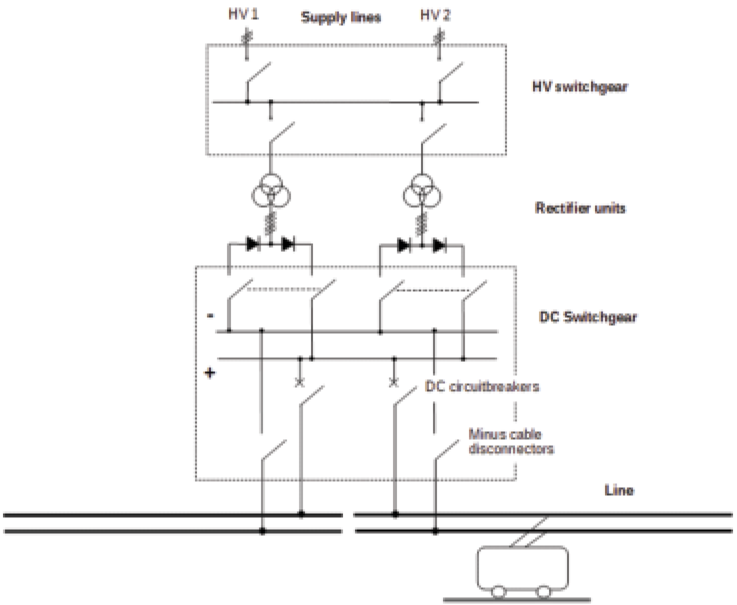

Fig. 4.11. Electrical structure of trolleybus substation

Fig. 4.12. Compact trolleybus substation, Brno, Czech Republic

Fig. 4.13. Equipment of trolleybus traction substation: HV switchgear (left), rectifier unit in compact design (middle), DC switchgear (right), Gdynia, Poland

Fig. 4.14. DC switchgear of trolleybus substation, Gdynia, Poland

4.2.1. Grounding of the trolleybus supply system

Initially (1930-1950) trolleybus routes were built in place of tram lines or as their extension. Therefore, the trolleybus networks used the existing tramway power supply. In this supply system, one pole (usually negative) of the trolleybus supply system is grounded (fig. 4.15 a). With the development of independent trolleybus systems, an alternative, isolated power system has become popular (fig. 4.15 b). In this system, the electric circuit of the trolleybus line is not connected with the earth potential.

One of the main disadvantages of the grounded power supply system is the relatively high risk of electric shock to passengers in the event of damage to the electrical insulation of the trolleybus. In a grounded system, one contact wire (usually negative) has a potential close to the earth potential. Consequently, the potential of the second wire (usually positive) is around 600 or 750 V. In an isolated supply system during standard conditions, the insulation resistance positive pole - earth is the same as the insulation resistance negative pole - earth. As a result of this, the voltage is distributed symmetrically on both wires and for a supply system of 600 V has the values +300 V (positive pole) and -300 V (negative pole). In normal operating conditions, the highest voltage of the traction wires in the insulated power supply system is half as high as in the grounded system, which reduces the danger resulting from electric shock.

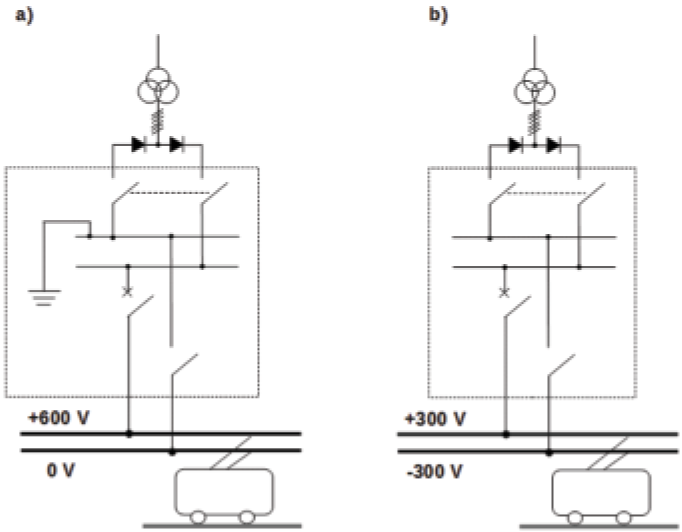

Fig. 4.15. Grounded (a) and isolated (b) supply system of trolleybus network

Isolated power supply systems are also characterized by a much lower level of the current of a single earth fault, which significantly increases the safety of the system's operation. This aspect is graphically presented on fig. 4.16, showing a situation with an insulation fault in the vehicle and earth short circuit with resistance R_{df}. The resistances of the DC supply cables, the overhead contact wires and the substation grounding resistance are significantly smaller than R_{df}, so the earth short circuit current can be estimated as:

$$I_d = \frac{U_{ts}}{R_{df}} \quad (4.1)$$

where U_{ts} is the output voltage of traction substation. Where the supply voltage is 600 V and the earth short circuit resistance is 1000 Ω, Id, the current will have a value of 0,6 A.

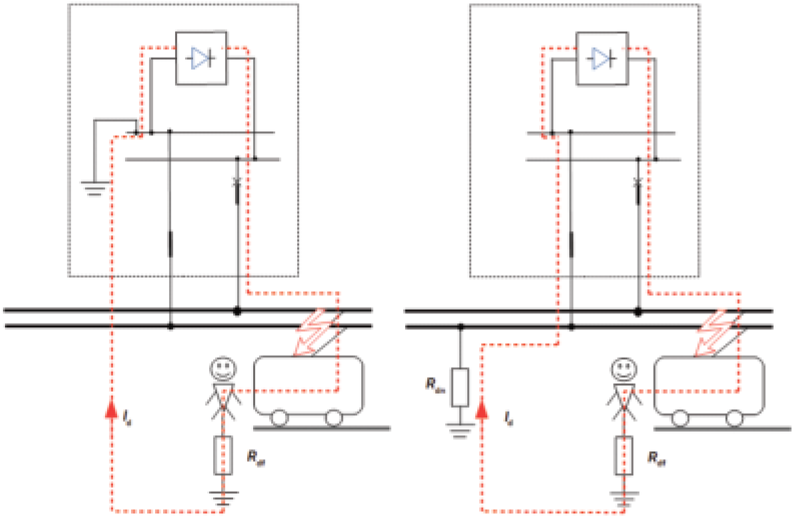

Fig. 4.16. The risk of electric shock in case of vehicle insulation failure in grounded (a) and isolated (b) supply system of trolleybus network

In the case of an isolated supply system, the earth short circuit current will conduct not through the substation grounding, but through the traction network insulation R_{dn} resistance of the opposite pole, so the value of I_d will be limited by R_{dn} accordingly:

$$I_d = \frac{U_{ts}}{R_{df} + R_{dn}} \tag{4.2}$$

In standard conditions during dry weather, the insulation resistance of the traction network is at a level of 500 kΩ or higher. During humid weather conditions this drops to around 50 kΩ. In this situation, the earth short circuit current will have a value of around 12 mA, which is decidedly less than in the case of a grounded system (0,6 A). During dry weather conditions this current will be much lower. Consequently, the isolated supply system is more secure from the point of view of electric shock protection. It should be emphasised that the R_{dn} value plays an important role in the reduction of the earth short circuit current. Therefore, in an isolated power supply system, it is very important to maintain the insulation of the overhead contact wires and power supply cables to the ground, keeping them in good condition.

Currently the isolated power supply system is the most popular method of supply for trolleybus networks. A significant number of trolleybus systems, previously working as earthed, have already been rebuilt on insulated networks. An important advantage of isolated systems is their greater reliability, because a single ground fault (e.g. damage to the insulation of supply cable) does not require switching off of the system. However, in this case the ground insulation fault must be removed as soon as possible, because it causes an increased risk of electric shock due to disturbances of voltage symmetry.

4.2.2. Common supply systems of trolleybus and tram network

In many cities, trams and trolleybuses transport systems operate in parallel, which raises questions about the possibility of their joint supply. This is most significant in situations where both systems have the same supply voltage. There are three possibility of supply for tram-trolleybus transportation systems:

- using common substations for tram and trolleybuses with common DC busbars (common DC potential),
- using common substations for tram and trolleybuses with separate DC busbars (different DC potentials of systems),
- using separate substations for both systems.

The use of common substations for tram and trolleybuses with common DC busbars is the simplest solution (fig. 4.17). To implement it, it is necessary to expand the DC switchboard with additional outputs for the trolleybus sections of line or use existing DC outputs. In this case, the trolleybus network is powered in a grounded system, which minimizes the risk of electric shock to passengers in the event of damage to the insulation of the electrical equipment in the vehicle.

In the case of common substations for tram and trolleybuses with separate DC busbars, the DC switchgear consists of two parts, one feeding the trolleybus network and the other for the tram system (fig. 4.18). Each of these parts is powered by separate rectifier units. This solution makes it possible to supply the trolleybus network in an isolated way. However, in many situations, this solution requires deep reconstruction of the existing tram substation, which makes it an unprofitable option. In many cases the costs of reconstructing the traction substations may be so high that it will be justified to consider the construction of separate substations for the trolleybus traction power supply. In addition, in many situations, the location of existing tramway substations is not optimal from the point of view of the trolleybus power supply of the traction network. Comparisons of the common tram and trolleybus systems is presented in the table 4.1.

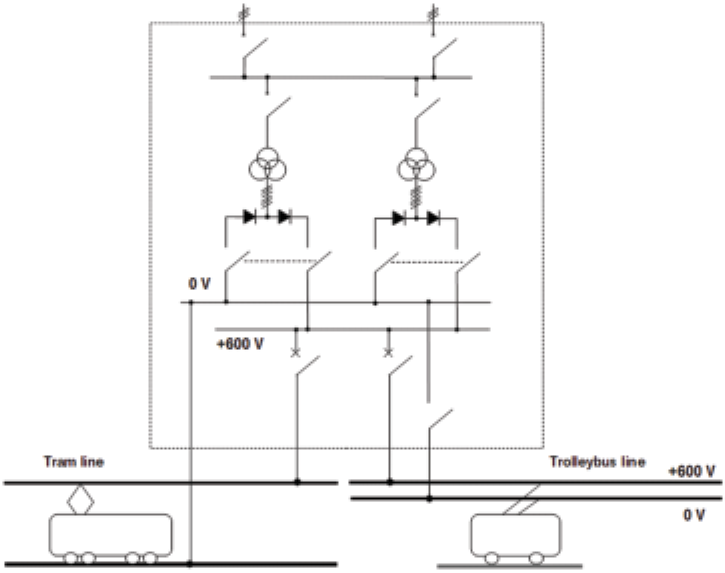

Fig. 4.17. Traction substation with common DC busbars for tram and trolleybus supply system

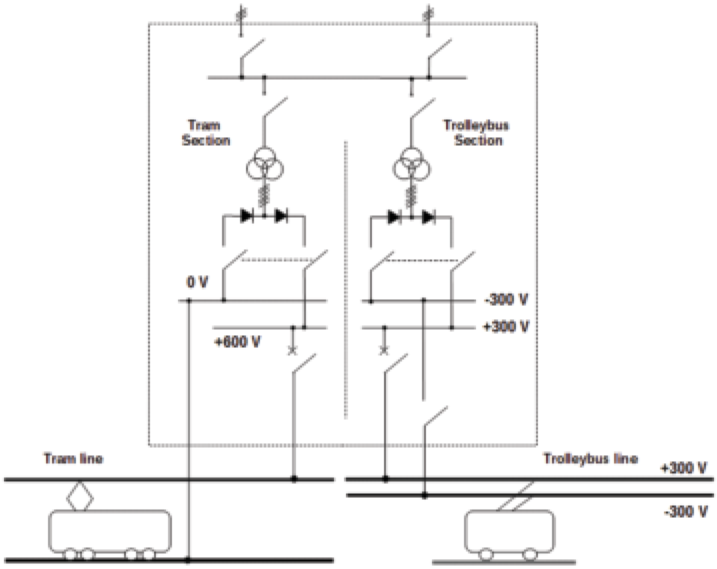

Fig. 4.18. Traction substation with separated DC busbars for tram and trolleybus supply system

Table 4.1. Comparison of common supply systems of trolleybus and tram network

	Substations with common DC busbars	Substations with separated DC busbars	Separated substations
Advantages	1) Low investment costs under favorable conditions 2) No new buildings required 3) Synergy of energy systems, e.g. improving of braking energy recovery usage	1) Isolated supply system of trolleybus network is possible 2) No new buildings required 3) It is possible to use different levels of supply voltage for tram and trolleybuses	1) Isolated supply system of trolleybus network is possible 2) Flexibility in construction of the trolleybus supply system 3) It is possible to use different levels of supply voltage for tram and trolleybuses
Disadvantages	1) Location of existing substation may not be optimal for trolleybus infrastructure 2) Only grounded supply system of trolleybus network is possible	1) Cost of the adapting of substation can be higher than construction of the new one 2) Location of existing substation may not be optimal for trolleybus infrastructure	1) Need to find location for substation

4.3. Insulation of vehicles

Trolleybuses are characterized by specific requirements regarding protection against electric shock. Unlike rail vehicles, trolleybuses travel on the asphalt roadway on pneumatic tires which have considerable resistance. The body of the trolleybus is thus isolated from the potential of the earth. This creates a risk of electric shock if the insulation of the electrical system in the vehicle is damaged (fig. 4.18). Standard protection solutions, like earthing, are therefore not applicable to trolleybuses. The basic means of protection against electric shock is the two-stage isolation of electrical devices (traction motor, converters) that operates with the potential of the traction supply voltage. It involves the use of two independent levels of insulation. One of them is the internal insulation in the device (e.g. insulation of motor winding), the second level is the insulation of the device from the construction of the vehicle (e.g. isolator between the traction motor and the body of the vehicle). The double insulation solution is shown on fig. 4.19. By control of the IE potential it is possible to monitor the condition of the insulation. Fig. 4.20 presents the trolleybus traction motor with visible isolators of the second level insulation between the traction motor and the vehicle chassis, and the insulator in the drive shaft.

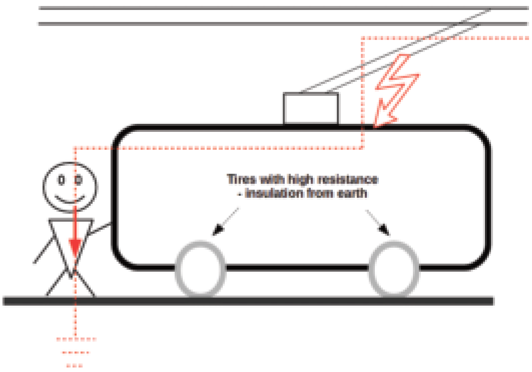

Fig. 4.18. Risk of electric shock in trolleybus

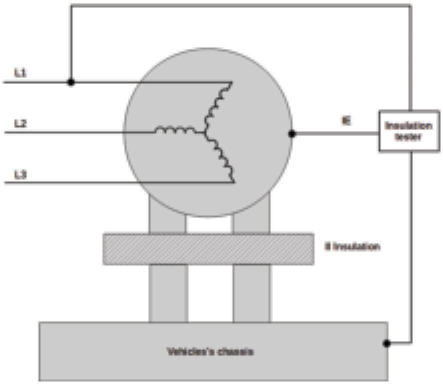

Fig. 4.19. Double insulation solution

Fig. 4.20. Trolleybus traction motors, the elements of second level insulation are visible

An exemplary diagram of a trolleybus insulation system is shown on fig. 4.21. The middle masses of the electrical equipment which work under traction voltage can be connected with the insulation monitoring system - insulation tester. This enables control of the insulation condition of the electrical equipment. Another protection device is the touch voltage detector. This controls the potential of the vehicle body using conductive strips which touch the roadway. Effective double insulation of traction batteries is complicated to implement, therefore they are often connected with the traction installation by means of a battery converter with internal double insulation (fig. 4.22). An alternative solution is an electrical installation with a main input converter, which enables the separation of the traction installation from the voltage potential of the supply system (fig. 4.23). This solution is very rarely used due to the high cost of the input converter, but it significantly simplifies the rest of the electrical installation.

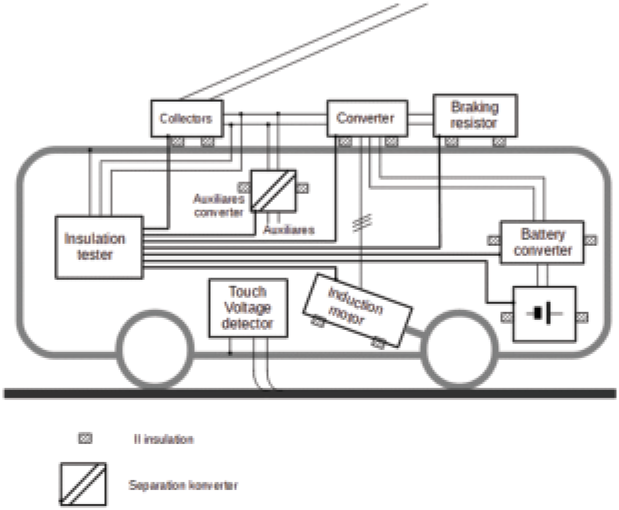

Fig. 4.21. Basic diagram of trolleybus electric insulation

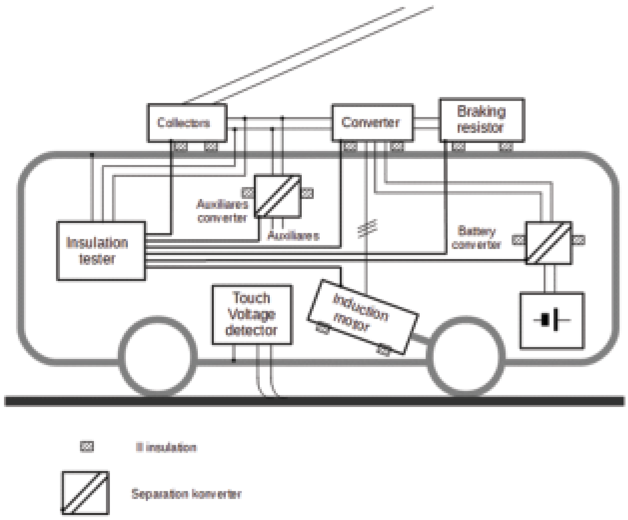

Fig. 4.22. Basic diagram of trolleybus electric insulation with separation traction battery converter

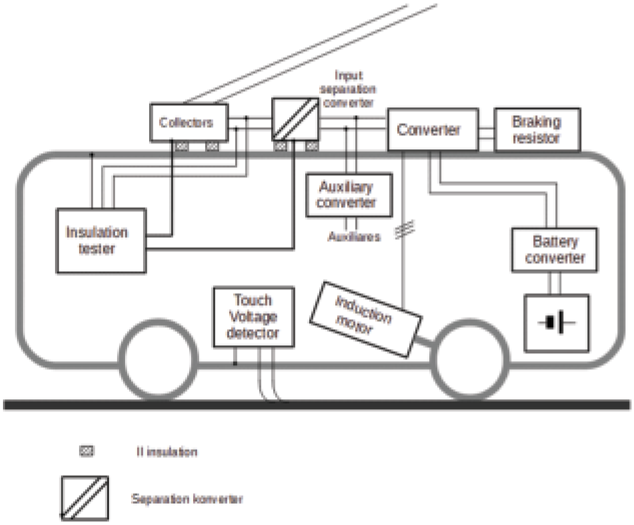

Fig. 4.23. Basic diagram of separated trolleybus electric equipment

4.4. Limitation of current collector

The current capacity of trolleybus collectors is one of the factors that limits the charging speed in dynamic charging systems. A trolleybus current collector diagram is shown on fig. 4.25. The collector tubes are usually made from insulation material (e.g. glass fiber). At the top of the collector tube there is there is a spoon - shoe body with a sliding contact - skid. The skid of the current collector is shown on figs. 4.24, 4.26. The electrical energy from the sliding contact is received by means of a wire placed inside the collector tube.

There are three main limitations on the current of the collector:

- the skid - contact between collector and traction wire,
- the current cable inside the tube,
- the connection point of the current cable and the spoon - shoe body of the sliding contact.

In practice, the first limitation is the most important. The current capacity mainly depends on the contact length skit - traction wire. In the case of skid material RH85M6 it is at level 16 - 20 A/mm [23]. The contact length is nominally 100 mm (fig. 4.26), so theoretically the current capacity should be at level 1600 A - 2000 A. In practice, the pressure of the slide is not equal, resulting in a contact surface of 30-40% of theoretic value. This gives a maximal average value of current of 400 - 500 V. This value is also confirmed by [18, 20]. The charging current limitations are greater during stopping periods, when cooling conditions are more difficult to maintain and the contact point in the collector can easily become overheated. The maximum current that can be received when the vehicle is stationary is at the level 150 A.

Fig. 4.24. The spoon - shoe body and skid of current collector [©Lekov, Faiveley Transport]

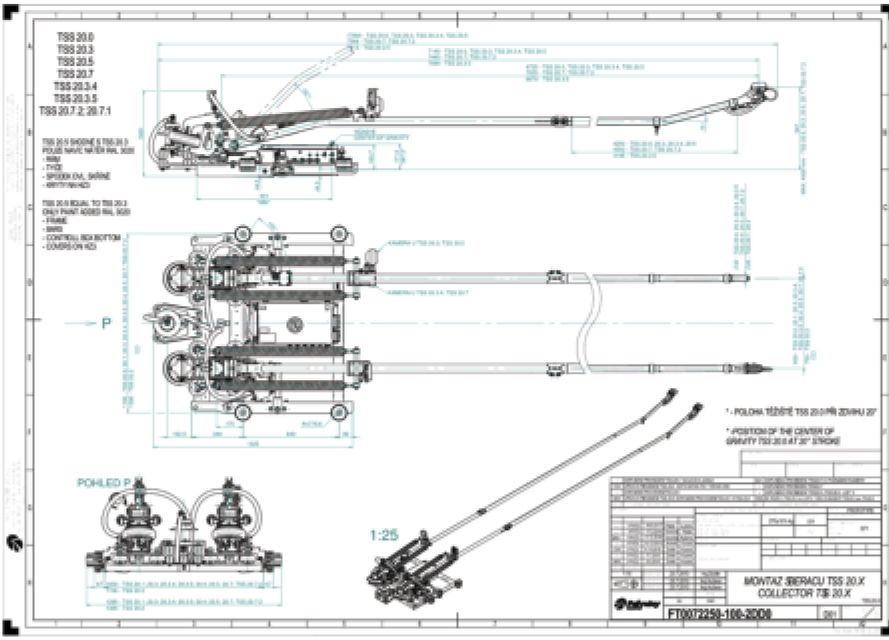

Fig. 4.25. The trolleybus current collector [© Lekov, Faiveley Transport]

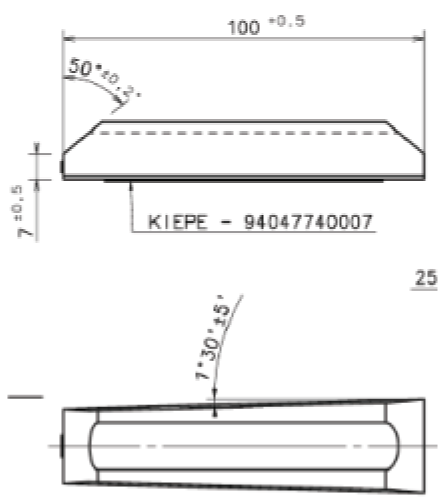

Fig. 4.26. The skid of trolleybus current collector [©Vossloh Kiepe, 18, 20]

5. LIMITATIONS OF CHARGING SPEED IN THE IMC SYSTEM

The length of sections accompanied by contact line must be sufficient to charge the traction batteries with energy at least equal to the energy necessary to cover the catenary-free section. Hence it is expected that the battery charging time will be minimised, which means that the charging power, i.e. the charging speed must be maximised.

5.1. Theoretical estimate of distance and time of traction battery charging

In the IMC system the energy accumulated in traction batteries along the section accompanied by contact line is the source of energy when a vehicle covers the section without the catenary. This can be shown by the dependence:

$$E_{ch} \cdot \eta = E_{dch} \tag{5.1}$$

where E_{ch} – energy transferred from the contact line to the battery during charging, E_{dch} – energy collected from the battery when covering the section without contact line, η – efficiency of the charging cycle. Assuming t_{ch} as the time of covering the contact line section, P_{ch} – the power of charging from the contact line, e – average consumption of energy by the vehicle, l – the total length of the route, l' – the route section under the contact line, the formula (1) can be presented as:

$$P_{ch} \cdot t_{ch} \cdot \eta = (l - l^1) \cdot e \tag{5.2}$$

Having taken into consideration the average speed of the vehicle driving along the contact line section (v), the formula can be transformed into:

$$P_{ch} \cdot \frac{l'}{v} \cdot \eta = (l - l^1) \cdot e \tag{5.3}$$

By transforming this dependence, the minimum degree l'' of covering the route with overhead contact line can be established:

$$l'' = \frac{l'}{l} = \frac{e}{\frac{\eta P_{ch}}{v} + e} \tag{5.4}$$

https://doi.org/10.2478/9783110645088-005

5.1.1. Assumption of energy consumption

The energy consumption of an electric vehicle significantly differs from a vehicle with an internal combustion engine, mainly due to the influence of external (weather) conditions. The internal combustion engine is characterized by a low efficiency level of 20 to 40 percent. It's a huge disadvantage on one side, because it increases the fuel consumption. But it has a good side: due to the low efficiency there is available a large amount of "waste heat" from the engine cooling that can be used to warm the interior of the vehicle. Although most of today's buses are equipped with an additional heat source (eg Webasto), the use of "waste heat" significantly reduces the amount of heating energy required. Electric drive is characterized by high efficiency and there is no "waste heat", so during winter we need to heat the interior, which is a big demand in terms of electricity consumption. In addition there may also be the need to power additional on-board subsystems such as ticketing machines and visual information systems. Given that passengers' expectations of driving comfort are increasing today, it is often the case that during winter the energy consumption for non-drawings exceeds traction consumption. For summertime periods, the need for air conditioning is gradually becoming standard equipment for public transport vehicles. The energy consumption problem is illustrated in Figure 5.1, which shows the consumption values of the Gdynia trolleybus during a one year period. Thus, it can be said that the energy consumption of an electric vehicle has a statistical form, and therefore we can express it with the histogram shown in Fig. 5.2.

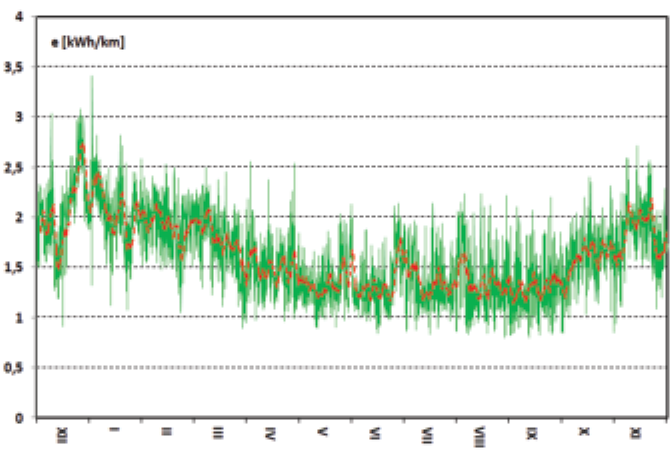

Fig. 5.1. Energy consumption of Gdynia's trolleybus in one year scale from December to November

The figure is based on registrations collected from one year period. They show the average energy consumption for traction purposes for individual journeys of sections between final terminuses (individual vehicle journeys). For further analysis it is useful to observe the characteristic of cumulative energy consumption means, energy consumption will be smaller than *e* with the probability *D* (Fig. 5.3).

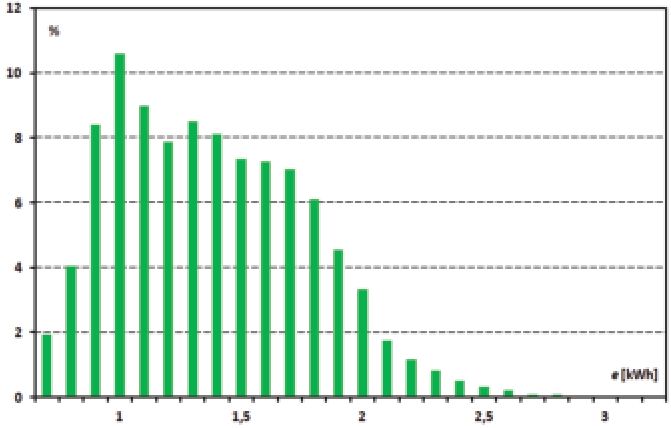

Fig. 5.2. Histogram of energy consumption of Gdynia's trolleybus from one year period

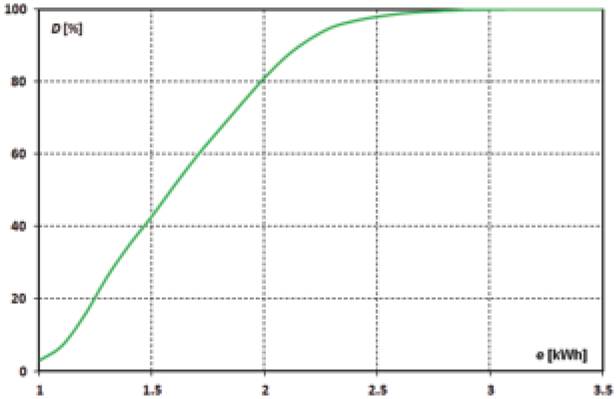

Fig. 5.3. The cumulative distribution of energy consumption of Gdynia's trolleybus from one year period

The average value of energy consumption is crucial from the point of view of the required degree of coverage with the traction network (fig. 5.1 - 5.2). However, due to the random nature of vehicle traffic and the occurrence of traffic congestion, in particular during rush hours, the average value of energy consumption on a short-term scale, during peak hours (on the level of 1 - 2 hours, corresponding to 10 - 20 km) may be higher than in a longer scale (full day, 150 - 200 km). This feature is presented on fig. 5.4. This mainly affects the required battery capacity, which will be discussed in the chapter 5.6.

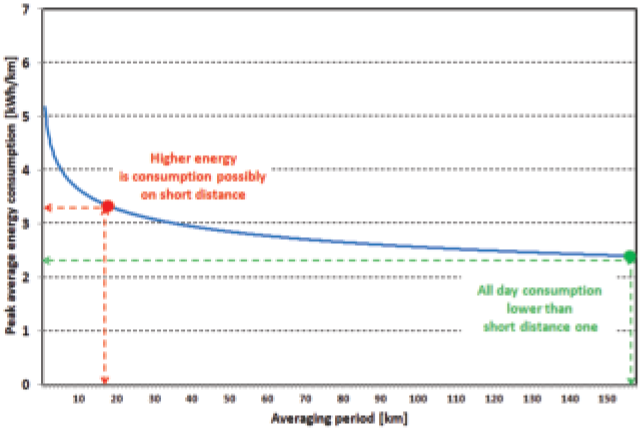

Fig. 5.4. The visualization of the maximal energy consumption during winter day in function of averaging distance (period)

5.1.2. Assumption of charging power and average velocity of the vehicle driving along the contact line section

The current capacity of trolleybus collectors is now the main factor which limits the charging speed in the IMC systems. Trolleybus current collectors are characterized by the maximum allowed average current of 500 - 600 A [5]. Limitations on charging current are even greater during stopping time, when the cooling conditions are more difficult and the contact point in the collector can easily become overheated. Therefore, the current collector load during stopping time should not exceed 100-150 A. The total load power P_{cc} transmitted by the current collector consists of power P_{veh} consumed by traction and non-traction needs of the vehicle, power P_{ch} of battery charging:

$$P_{cc} = P_{veh} + P_{ch} \tag{5.5}$$

so, the value of charging power can be described as:

$$P_{ch} = P_{cc} - P_{veh} \tag{5.6}$$

Maximal power P_{cc} transmitted by current collectors depends on the nominal voltage U_{tn} of the traction network and the maximal value I_{cc} of the current collectors value:

$$P_{cc} = U_{tn} \cdot I_{cc} \tag{5.7}$$

Because the maximal collectors current has different value while moving (I_{cc-m}) and while stopping (I_{cc-s}), the average value of maximal charging power can be described as:

$$P_{ch} = (U_{tn} \cdot I_{cc-m} - P_{veh-m}) \cdot t_m + (U_{tn} \cdot I_{cc-s} - P_{veh-s}) \cdot t_s \tag{5.8}$$

where: P_{veh-m} - vehicle's power during movement, P_{veh-s} - vehicle's power during stopping, t_m, t_s - participation of movement time and stopping time in total driving time.

In table 5.1 are presented the average values of trolleybus traffic indicators in the central part of Gdynia and two districts. Moreover, there are shown the maximal values of charging during movement (P_{ch-m}), stopping (P_{ch-s}) and average charging power (P_{ch}). Assuming the energy consumption at 3,2 kWh/km the minimum degree I'' of covering the route with overhead contact line was calculated.

Table 5.1. The average values of trolleybus traffic indicators in central part of Gdynia and two districts, and calculated values of charging parameters

	Centre		District I		District II	
	Sept.	Feb.	Sept.	Feb.	Sept.	Feb.
t_m	0,63	0,65	0,67	0,70	0,73	0,77
t_s	0,37	0,35	0,33	0,30	0,27	0,23
V [km/h]	13,01	14,28	16,46	18,52	17,53	19,57
P_{veh-m} [kW]	20,80	39,53	24,78	44,52	23,16	40,60
P_{veh-s} [kW]	5,48	31,59	4,96	34,73	5,76	40,95
Calculated values						
P_{ch-m} [kW]	275	255	279	260	277	259
P_{ch-s} [kW]	85	55	85	58	84	49
P_{ch} [kW]	212	195	206	189	224	210
I'' for U_{tn}=600 V	0,20	0,23	0,17	0,19	0,20	0,23
I'' for U_{tn}=750 V	0,16	0,19	0,14	0,16	0,16	0,19

5.2. Statistical analysis of dynamic charging aspects

The energy consumption of the vehicle is of a statistical nature (fig. 5.1 - 5.3), and therefore also the limit parameters for the dynamic loading system can also be analyzed from a statistical point of view. The calculations presented in the table 5.1 have been made for the maximum value of energy consumption in winter, however, assuming a level of certainly less than 100%, it is possible to work the dynamic charging system by a shortened section of the overhead contact line. In other words, it is possible to analyze the reliability of the dynamic charging system, with less coverage by the traction network than the one determined on the basis of maximum energy consumption. It can be realized on the basis of the cumulative distribution of vehicle energy consumption (fig. 5.3) converted by equitation (5.4). These calculations were realized for 3 variants of charging power:

- $P_{ch\text{-}m}$ = 70 kW, $P_{ch\text{-}s}$ = 70 kW which equals the charging power applied in trolleybuses Solaris Trollino 12 operated in Gdynia,
- $P_{ch\text{-}m}$ = 200 kW, $P_{ch\text{-}s}$ = 50 kW which equals the maximal charging power shown in table 5.1, calculated for loading of the collectors with currents 500 A and supply voltage 600 V,
- $P_{ch\text{-}m}$ = 250 kW, $P_{ch\text{-}s}$ = 70 kW which equals the maximal charging power shown in table 5.1, calculated for loading of the collectors with currents 500 A and supply voltage 750 V,

The calculations were carried out with the assumption an average speed of driving speed at the levels: 13 km/h, 16 km/h and 19 km/h. The results are shown on fig. 5.4 - 5.6. In the case of coverage with a traction network less than optimal, it will be necessary to have an additional stop on the end terminus for additional recharging of the battery.

$$t_{add} = \frac{E_{dch} - E_{ch} \cdot \eta}{P_{ch-s}} \tag{5.9}$$

E_{ch} – energy transferred from the contact line to the battery during charging, E_{dch} – energy collected from the battery when covering the section without contact line, η – efficiency of the charging cycle. Assuming the notifications the same like as in quotations (5.1-5.4), the formula can be converted to:

$$t_{add} = \frac{(l - l') \cdot e - P_{ch-m} \cdot \frac{l'}{v} \eta}{P_{ch-s}} \tag{5.10}$$

replacing l' by quotient $l{*}l''$:

$$t_{add} = \frac{(l - l \cdot l'') \cdot e - P_{ch-m} \cdot \frac{l \cdot l''}{v} \eta}{P_{ch-s}} \tag{5.11}$$

it is possible to define the additional charging time at the terminus for unitary distance of transportation route [min/km]:

$$\frac{t_{add}}{l} = \frac{(1-l'')e - P_{ch-m}\frac{l''}{v}\eta}{P_{ch-s}} \tag{5.12}$$

The cumulative distribution of additional charging time was calculated for the following variants:

- $P_{ch\text{-}m}$ = 70 kW, $P_{ch\text{-}s}$ = 70 kW, l''=0,3,
- $P_{ch\text{-}m}$ = 200 kW, $P_{ch\text{-}s}$ = 50 kW, l''=0,15,
- $P_{ch\text{-}m}$ = 250 kW, $P_{ch\text{-}s}$ = 70 kW, l''=0,1.

Results of the calculation are shown on fig. 5.5 - 5.10.

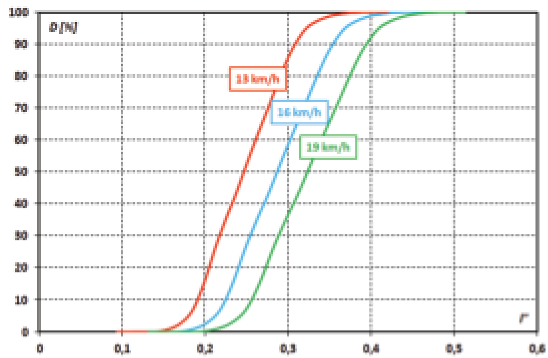

Fig. 5.5. The cumulative distribution of successful charging probability in function of covering rate l'' for charging power 70 kW

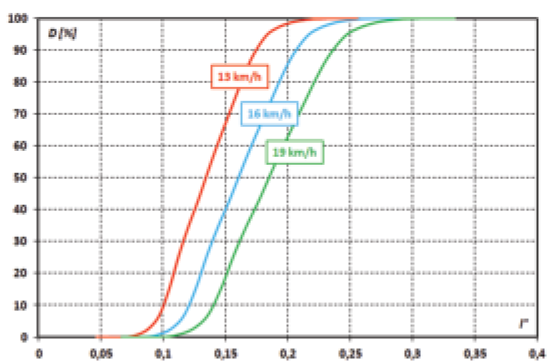

Fig. 5.6. The cumulative distribution of successful charging probability in function of covering rate l'' for charging power 200 kW

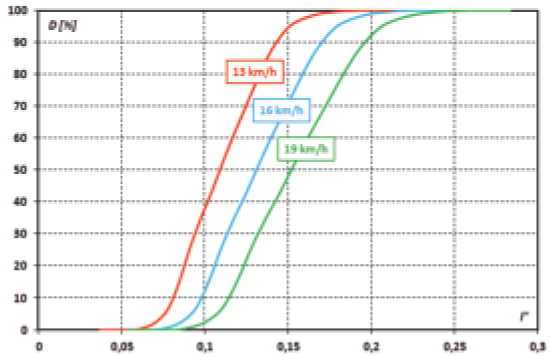

Fig. 5.7. The cumulative distribution of successful charging probability in function of covering rate l^* for charging power 250 kW

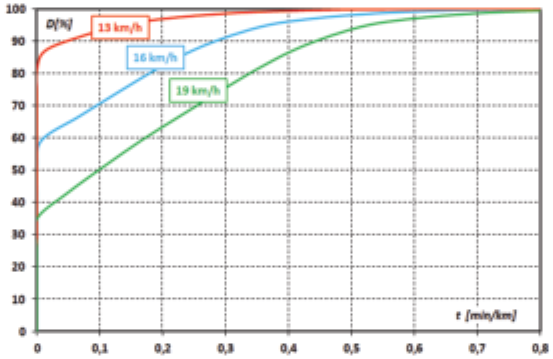

Fig. 5.8. The cumulative distribution of additional charging time on terminus in case of charging power 70 kW and covering rate $l^*=0,3$

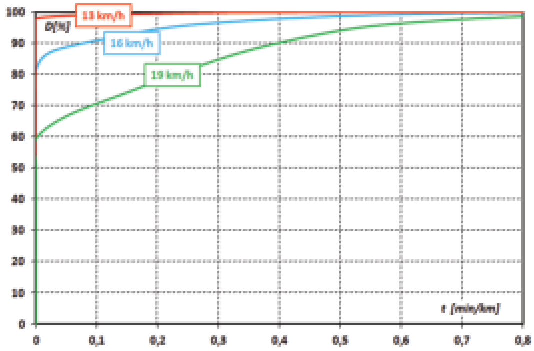

Fig. 5.9. The cumulative distribution of additional charging time on terminus in case of charging power 200/50 kW and covering rate $l^*=0,15$

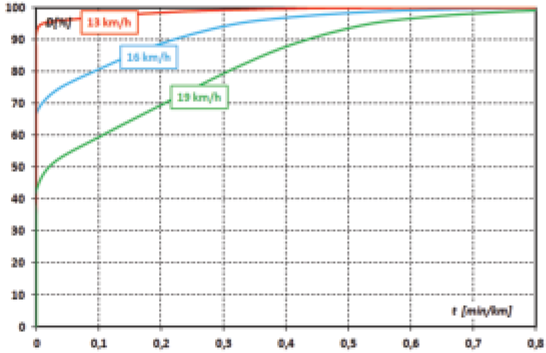

Fig. 5.10. The cumulative distribution of additional charging time on terminus in case of charging power 250/70 kW and covering rate l^*=0,15

The key parameter affecting energy consumption is the outside temperature, which is illustrated in fig. 5.11. In this way, the temperature influences the required minimum degree of coverage with the overhead catenary network (fig. 5.12) and eventually additional charging time during stopping (fig. 5.13).

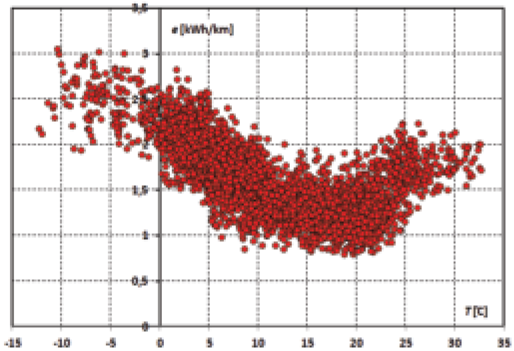

Fig. 5.11. Scatter chart of average energy consumption of trolleybuses in Gdynia in function of external temperature

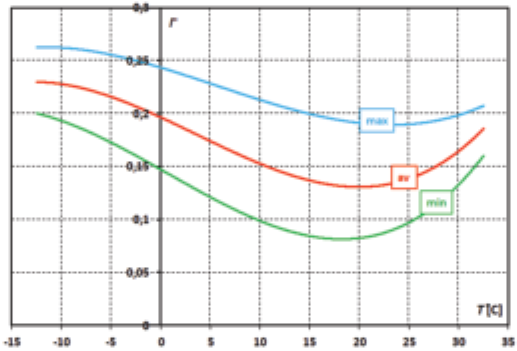

Fig. 5.12. The maximum, average and minimum value of covering rate l^* for charging power 200 kW in function of ambient temperature

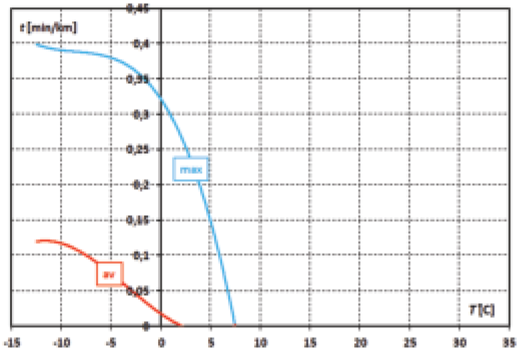

Fig. 5.13. The maximum and average rate of additional charging time on terminus in case of charging power 200/70 kW and covering rate l^*=0,20

5.3. Measurements performed within Gdynia trolleybus network

Since 2009 PKT Gdynia has been utilizing trolleybuses equipped with auxiliary battery drive. Originally the vehicles were equipped with nickel-cadmium batteries with a capacity of 16 kWh. Since 2015 vehicles with high-capacity lithium-ion batteries with capacities of 40 kWh and 69 kWh have been introduced into use. As a result, a considerable amount of operational experience has been acquired.

Due to its excellent operational characteristics, the utilization of autonomous trolleybus drive is not only suitable in emergency situations, but also when there is insufficient stock on the Gdynia bus routes. In such situations battery trolleybuses often function on the routes, charging via the overhead contact line covering the common sections of the routes.) This was done on the largest scale from the 29th June to the 1st July 2016 when, as a consequence of the organization of the Open'er Festival, there was a considerable shortage of vehicles for bus transport. Trolleybuses equipped with high-capacity lithium-ion batteries were used to service some bus routes in Gdynia and Sopot, for example routes S, 159 and 172. Using their auxiliary drive, the vehicles were able to cover long sections of the routes, sometimes as much as 29 km. This allowed for the creation of a measurement database covering the operation of battery trolleybuses with considerable use of auxiliary drive and subsequently applying this data as guidelines when determining the dimensions of public transport routes based on the IMC.

Table 5.2. Technical data of traction batteries in Solaris Trollino 12 trolleybuses

Number of battery modules	3, connected in parallel
Total capacity of batteries	69 kWh
Technology	lithium-ion
Producer	Impact Clean Power / Ener Del
Single module capacity	23 kWh / 36 Ah
Maximum voltage of a module	728 V
Maximum continuous output power of a module	64 kW
Maximum continuous power of module charging	38 kW

Fig. 5.14. Rear part of a Solaris Trollino 12 trolleybus, 3 battery modules (black boxes) and the charging system (a grey box in the upper part of the apparatus) are visible

Registered data from three of the newest Solaris Trollino 12 trolleybuses, belonging to PKT Gdynia's stock (fig. 5.14, 5.15) have been used for analysis. The technical data of battery systems have been presented in Table 5.2.

Fig. 5.15. Interior of the rear part of a Solaris Trollino 12 trolleybus. The vertical casing containing battery modules is visible

5.3.1. Energy consumption of auxiliaries

The auxiliary systems comprise the electrical equipment of the vehicle which is not directly used in the generation of traction force. The following elements can be included in auxiliary systems:

- compressor and hydraulic pump motors,
- supply of low voltage equipment,
- air conditioning,
- heating.

In practice, the last two elements form the main part of the auxiliary load, with heating in particular being a major factor. A significant increase in the efficiency of electric drive systems has been observed over recent years, leading to a reduction in energy consumption for traction purposes in electric vehicles. On the other hand, passenger expectations regarding cabin temperature comfort are contributing to an increase in power expenditure on heating devices. The result of these two factors is an increase in the relative share of energy consumption for heating purposes in the electric traction in relation to the total energy consumption. This is especially important for battery vehicles that are powered from a source with limited capacity.

Based on the heat flow equations, the amount of thermal energy Q transferred in a time t in the steady state and with a small temperature difference ΔT on both sides of the partition can be described by the dependence:

$$Q = \lambda \frac{S \cdot \Delta T \cdot t}{d} \tag{5.13}$$

where:

d - thickness of the partition,

λ - thermal conductivity coefficient.

The power used for heating the vehicle is equal to the quotient of the amount of thermal energy transferred outside the vehicle and the time at which it was transferred. Assuming that the heat dissipation takes place only by transferring heat energy through the side surfaces, roof and chassis, after converting dependence (5.13), the heating power necessary to maintain a constant temperature inside the vehicle can be described as:

$$P(\Delta T) = c \cdot \Delta T \tag{5.14}$$

where:

c - coefficient depending on thermal conductivity and dimensions of side surfaces, roof and vehicle chassis.

The linear nature of the dependence (5.14) is confirmed by the scatter of the scatter graph of non-traction needs as a function of the temperature difference inside - outside presented on the figure 5.16. Unitary energy consumption per km on auxiliary purposes depends on the average velocity v_{av} of the movement and can be described by formula:

$$e(\Delta T) = \frac{P(\Delta T)}{v_{av}} \tag{5.15}$$

The significance of the issue is illustrated in Fig. 5.16, which presents the mean unitary total energy consumption per km of a trolleybus as a function of the temperature difference inside versus outside. The scatter graph illustrating the value of non-traction needs per distance as a function of the temperature difference inside - outside is presented on the figure 5.17. Graphs are based on measurements carried out in trolleybus system of Gdynia in 12 meters Solaris Trollino 12 vehicles..

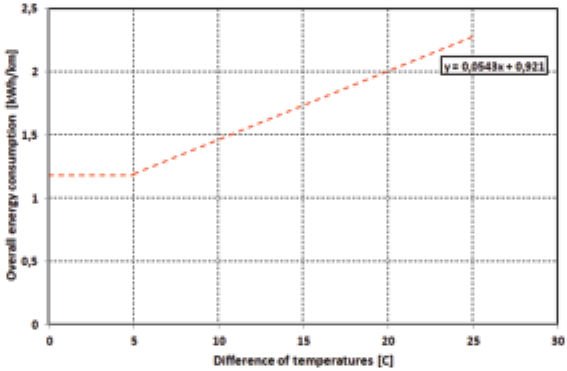

Fig. 5.16. Overall vehicle power consumption in function of difference between ambient and internal temperature

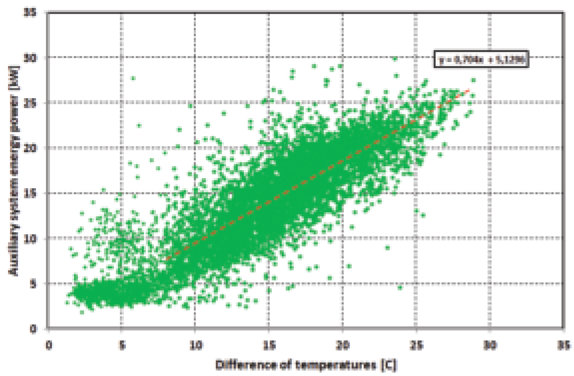

Fig. 5.17. Scatter chart of auxiliary power consumption in function of difference between ambient and internal temperature

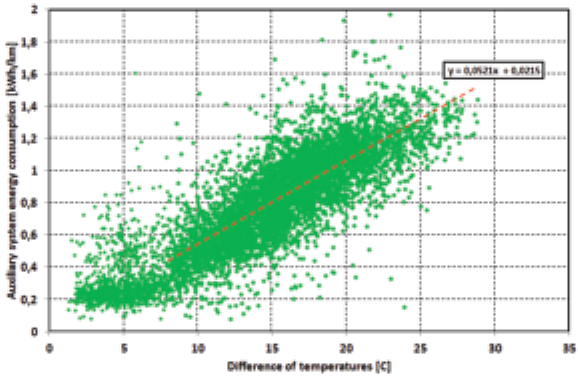

Fig. 5.18. Scatter chart of auxiliary energy consumption related to distance in function of difference between ambient and internal temperature

Under standard operating conditions, the non-traction energy unitary consumption is up to 1,2 kWh/km, which accounts for a total energy consumption of around 2,5 kWh/km. This consumption may be higher in case of disturbances caused by congestion, what results in a decrease in the average speed of the vehicle. The effect of this may be an increase of energy demand for non-traction purposes according to the formula (5.15). It illustrates high values of unitary energy consumption on non-traction needs of several measurements shown in picture 5.18, which exceeds 1,6 kWh/km. This requires a significant increase in battery capacity. On the other hand, periods of significant demand occur very rarely (less than 1% of registered journeys). For this reason, it is recommended to use heating power control. This involves reducing the heating power if the battery is discharged under a certain level. For example, a reduction of the inside temperature of the vehicle by 8 degrees Celsius does not cause a significant decrease in travel comfort (during winter weather, the passengers are warmly dressed), while this reduces the energy consumption by 0,5 kWh/km. This solution can be used in the event of non-standard traffic situations and avoids excessive energy consumption.

5.3.2. Analysis of overall energy consumption

Based on the measurement data obtained at the time when bus routes were serviced by battery trolleybuses (29th June - 1st July) energy consumption in individual operational modes has been established. The values for the catenary and battery operational modes, as well as the values of energy consumption for traction purposes and the total energy consumption value have been set. Energy consumption for catenary supply with fast battery charging switched on has also been established (Table 5.3).

Table 5.3. Average power parameters of battery trolleybuses servicing bus routes from 29th June to 1st July 2016

	Catenary operation	Battery operation
Total energy consumption	No battery charging: 1,45 kWh/km Taking into account battery charging energy in fast charging mode: 4,06 kWh/km	1,27 kWh/km
Energy consumption for traction purposes with recuperation taken into account	0,84 kWh/km	1,01 kWh/km
Energy consumption for traction purposes (recuperation not taken into account)	1,45 kWh/km	1,6 kWh/km

5.3.3. Measurement estimate of distance and charging time for traction batteries

When servicing bus routes, the trolleybuses covered, on battery supply, sections of route varying in length from 0,5 km to 29 km. Battery charging from the traction network took place during the operation. This allowed for the collection of data making it possible to establish boundary parameters of both battery and catenary drive for the vehicles charged in the IMC system:

- recording the drive with traction battery supply allowed for the establishment of the range of a vehicle in autonomous operation;
- recording the drive with traction network supply and simultaneous charging of traction batteries allowed for the establishment of the parameters of the traction battery charging process.

Based on the above data, three basic analyses of the obtained data have been performed:

1) The dependence between the length of autonomous drive l_{aut} and the degree of battery discharging DOD resulting from it has been established based on the analysis of the sections covered by the vehicle with battery supply (Fig. 5.19).

2) The dependence between the degree of battery discharging DOD and the required time for charging batteries t_{ch} from the catenary has been established based on the route section covered by the vehicle with catenary supply (Fig. 5.20)

3) Additionally, the dependence between the degree of traction battery discharging DOD and the distance l_{ch} required for battery recharging has been established based on the above data (Fig. 5.21).

Assuming a constant energy consumption e, the formula with have the degree of battery discharging DOD can be described as:

$$DOD = \frac{l_{aut} \cdot e}{C_{bat}} \tag{5.16}$$

where C_{bat} means the capacitance of the batteries. This formula can be presented as linear function:

$$DOD = k_1 \cdot l_{aut} \tag{5.17}$$

where:

$$k_1 = \frac{e}{C_{bat}} \tag{5.18}$$

In the case of constant average charging power P_{ch} charging time can be described as following:

$$t_{ch} = \frac{DOD \cdot C_{bat}}{P_{ch} \cdot \eta} \tag{5.19}$$

η - efficiency of charging process. Assuming a constant velocity v of movement on wired section, the charging distance l_{ch} can be described accordingly:

$$l_{ch} = \frac{v \cdot DOD \cdot C_{bat}}{P_{ch} \cdot \eta} \tag{5.20}$$

and the corresponding linear function:

$$l_{ch} = k_2 \cdot DOD \tag{5.21}$$

where:

$$k_2 = \frac{v \cdot C_{bat}}{P_{ch} \cdot \eta} \tag{5.22}$$

These dependencies have a linear character, which is confirmed by the figures 5.18 - 5.20. The linear regression method was used to obtain the values of linear coefficients, the value of k_1 is 1,85 and value of k_2 is 0,26.

Analysis 1 (fig. 5.19) makes it possible to established the battery capacity required for covering a given route section, while analyses 2 (fig. 5.20) and 3 (fig. 5.21) establish for establishing the parameters of the catenary section where battery charging takes place. In the IMC system the route section under the contact line l' equals the charging distance l_{ch}. Analogically as in chapter 5.1, the ratio between charging distance and the total length of movement during cycle charging - discharging can be used for setting the minimum degree l'' of covering the route coverage with overhead contact line:

$$l'' = \frac{l_{ch}}{l_{ch} + l_{aut}} \tag{5.23}$$

and consequently:

$$l'' = \frac{k_2 \cdot DOD}{k_2 \cdot DOD + \frac{DOD}{k_1}} = \frac{k_2}{k_2 + \frac{1}{k_1}} \tag{5.24}$$

For conditions of autonomous driving in Gdynia, the minimum degree of covering the route with overhead contact line is 32%.

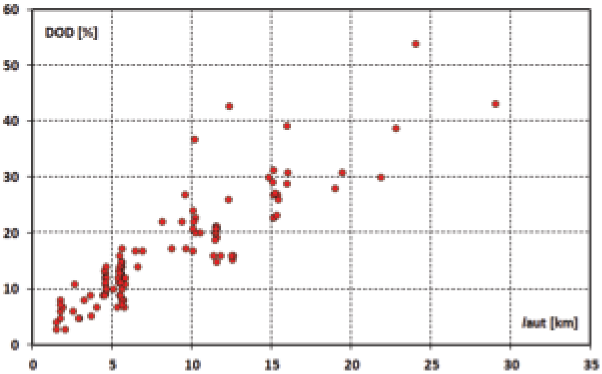

Fig. 5.19. Dependence between the length of autonomous drive and battery discharging

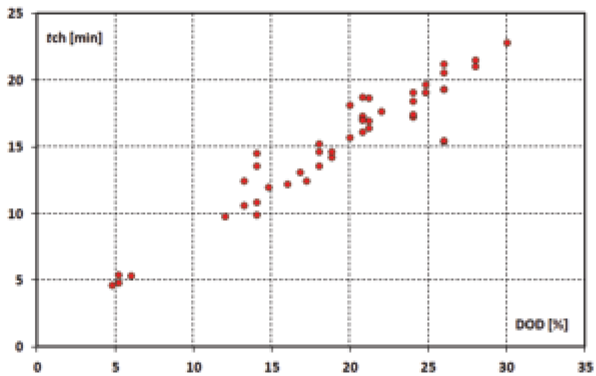

Fig. 5.20. Dependence between the degree of battery discharging and the time required for charging batteries from the catenary

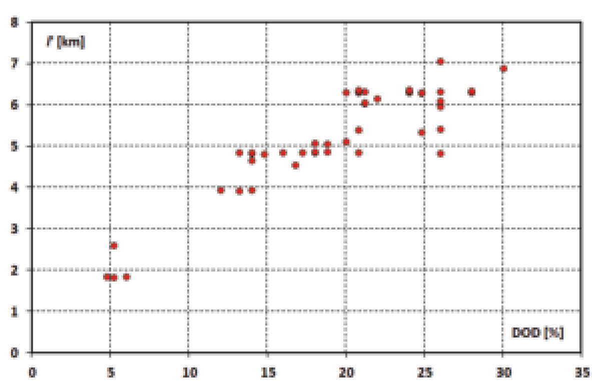

Fig. 5.21. Dependence between the degree of traction battery recharging and the distance required for battery recharging

The presented values are based on experiences from Gdynia, which is operating trolleybuses with battery charging power 69 kW and average energy consumption during measuring period was 1,3 kWh/km. Thanks to the linear dependence (5.15) - (5.24), the obtained results may be used to estimate the charging times and the minimum relative length of a route under the catenary for other operational conditions. Assuming the test condition as the reference values, it is possible to estimate the k_1 and k_2 coefficient for another charging power P_{ch_e} and energy consumption e_e:

$$k_{1\_e} = k_1 \frac{e_e}{e} \tag{5.25}$$

$$k_{2\_e}{}^1 = k_2 \frac{P_{ch}}{P_{ch\_e}} \tag{5.26}$$

Accordingly, the equitation (5.24) can be modified as:

$$l_e{}^* = \frac{k_2 \frac{P_{ch}}{P_{ch\_e}}}{k_2 \frac{P_{ch}}{P_{ch\_e}} + \frac{e}{k_1 \cdot e_e}} \tag{5.27}$$

where P_{ch} and e means the reference values (69 kW, 1,3 kWh/km).

Table 5.4. Comparison of charging parameters

	Current state	Increase of charging power	
		Up to 100 kW	Up to 160 kW
Minimum coverage of the route with catenary, when the energy consumption is 1,3 kWh/km (in springtime)	32 %	25 %	17 %
Minimum coverage of the route with catenary, when the energy consumption is 3,0 kWh/km (in wintertime)	53 %	35 %	25 %

Table 5.4 presents the comparison of estimated relative lengths of transportation route coverage by overhead catenary for different operational conditions and different charging powers. There are two average values of charging power analyzed:

- 100 kW,
- 160 kW, which equals the charging with power 200 kW during motion and 70 kW while standing.

The values of energy consumption are at the level:

- 1,3 kW/km for average spring conditions,
- 3,0 kWh/km for extreme winter conditions.

5.3.4. Measuring analysis of battery charging possibilities while travelling

Registrations of energy usage while travelling can be used to simulate the charging and discharging cycle of the battery in a dynamic charging system. This simulation consists of two stages:

- charging cycle, passing through a fixed length network section with an overhead catenary,
- discharging cycle, passing through an autonomous section.

For the simulation of discharging, measurement data of the actual load of energy consumption by the vehicle are used. The unloading simulation is performed until the charging energy accumulated during the network section is fully utilized. This allows for the determination of the length of the autonomous section. This cycle is repeated for many different registration data. After statistical analysis, it is then possible to determine the minimum degree of coverage for the traction network.

In the charging cycle, the state of charge E_{bat} of the traction battery is based on the state of charge in the previous iteration and charging power P_{ch}:

$$E_{bat}(t_n) = E_{bat}(t_{n-1}) + P_{ch} \cdot \Delta t \qquad (5.28)$$

In the case of a vehicle with a central DC separation converter with power P_{conv}, the formula is as follows:

$$E_{bat}(t_n) = E_{bat}(t_{n-1}) + P_{conv} \cdot \Delta t - P_{veh}(t_n) \cdot \Delta t \qquad (5.29)$$

where P_{veh} is the vehicle energy consumption. Δt indicates the step of the iteration, which is the same as the interval of registration (1 second). The value of P_{ch} or P_{conv} depends on the state of the vehicle due to reduced current capacitance of the collector. While the vehicle is standing the value is lower. In every step of the calculations the actual driven distance s is calculated:

$$s(t_n) = s(t_{n-1}) + v(t_n) \cdot \Delta t \qquad (5.30)$$

where v is the vehicle velocity. Where distance s is greater than the length of the cathenary section l_{troll} then autonomous mode (discharge) starts. In the discharging cycle, the state of charge E_{bat} of the traction battery is based on the state of charge in the previous iteration and charging power P_{ch}:

$$E_{bat}(t_n) = E_{bat}(t_{n-1}) + P_{veh}(t_n) \cdot \Delta t \quad (5.31)$$

the cycle calculations are finished when the energy of the battery is at zero level. The main outcomes of the calculations are the length of the autonomous running section and the ratio between the length of the cathenary section and the total running length during the cycle. The scheme of simulation model is shown on fig. 5.22.

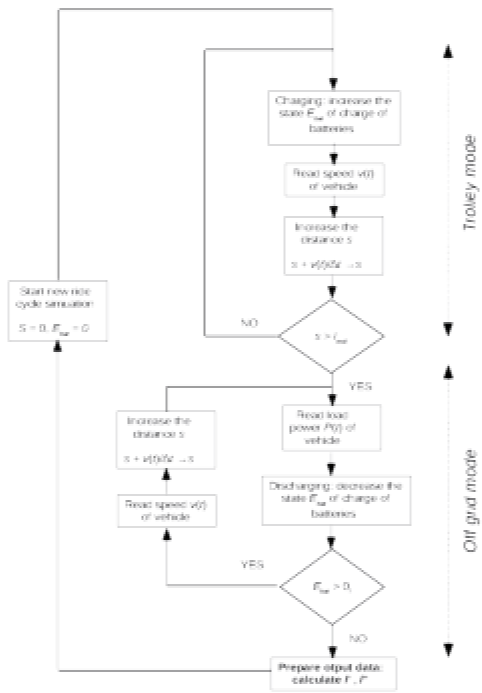

Fig. 5.22. The scheme of simulation model of Dynamic Charging

A simulation based on real measurement data allows for:

- consideration of the real travelling time and stop time whilst in trolley mode,
- taking into account the real value of energy consumption from traction batteries during autonomous driving.

The simulation is designed for two different vehicle propulsion system assemblies:

- having a charger with constant charging power,
- having a central separation converter with constant power – in which case the charging power depends on the power consumed by the vehicle at a particular moment.

Due to the limited current capacity of trolleybus collectors, the charging power is reduced while the vehicle is standing. Three different scenarios were taken into account for this:

- immediate reduction of charging power to 80 kW after vehicle stopping,
- reduction of charging power to 80 kW in 30 seconds after vehicle stopping,
- reduction of charging power to 80 kW in 60 seconds after vehicle stopping.

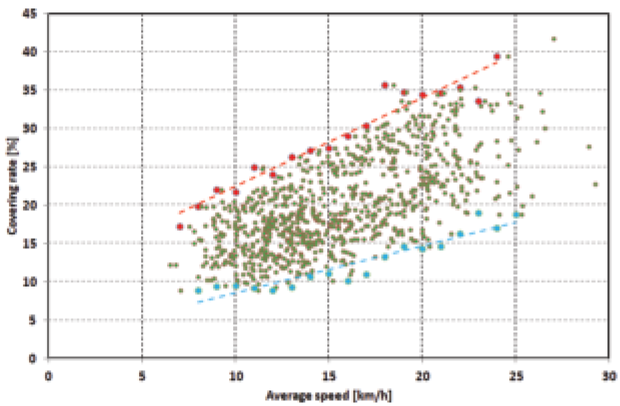

Fig. 5.23. Scatter plot of simulation results in function of average speed in charging section: charging power 120 kW

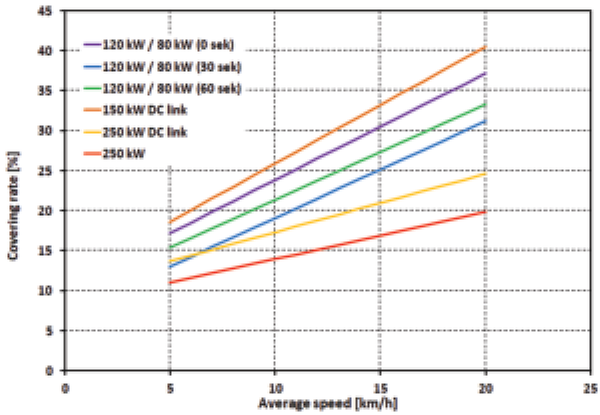

Fig. 5.24. Minimal covering rate for the worst cases for several charging methods (time value in brackets indicates the time after which the charging power is reduced)

Fig 5.23 shows an exemplary scatter plot of the simulation results in function of the average speed in the charging section, for a charging power of 120 kW. Each point marks the result of one driving cycle calculation. It is possible to see the envelope of data for the best case (blue marked points) and the worst case (red marked points). This allows for the definition of the approximation line (red dotted line) which indicates the minimal rate of coverage of the transportation route by centenary in function of speed. This procedure was repeated for several charging methods. The results are shown on fig. 5.24.

5.3.5. Estimation of IMC system parameters for articulated vehicle

Energy consumption of articulated vehicles is greater than in the case of single vehicles. There are two main reasons for this:

- greater weight of articulated vehicle,
- greater non auxiliary consumption needs in articulated vehicles, mostly caused by the higher power requirements of heating.

Table 5.5. Comparison of overall energy consumption of trolleybuses in Lublin

	Energy consumption of standard vehicle [kWh]	Energy consumption of articulated vehicle [kWh]	Relation between energy consumptions
January	2,58	3,09	1,2
February	2,26	2,59	1,14
March	1,86	2,19	1,18
April	1,76	2,13	1,21
May	1,61	1,92	1,19
June	1,62	1,78	1,1
July	1,66	1,79	1,08
August	1,7	1,81	1,06
September	1,63	1,91	1,17
October	1,85	2,26	1,22
November	2,21	2,54	1,15
Overall	1,80	2,18	1,16

The weight of articulated vehicles is around 30% greater than standard vehicles. The volume of the passenger space of an 18-meter articulated vehicle is 50% larger than a standard one. This results in a 30 - 40% higher energy consumption for an articulated vehicle. The comparison of overall energy consumption of trolleybuses in Lublin (Poland) with traction energy needed in trolleybuses in Ostrava (Czech Republic) is shown in tables 5.5 and

5.6. In the first case the overall energy consumption is 20% greater for an articulated vehicle than in standard one. Data from Ostrava shows that traction energy consumption is greater in an articulated vehicle by 40%.

Table 5.7 presents a comparison of minimal catenary coverage rate in the operation of both standard and articulated vehicles. The calculations were made with an assumption of maximal energy consumption of 3,0 kWh/km for a standard vehicle and 3,9 kWh/km for an articulated one. Calculations were made according to formula (5.4) for charging power 70 kW, 200 kW (70 kW while standing) and 250 kW (100 kW while standing).

Table 5.6. Comparison of energy for traction needs consumption of trolleybuses in Ostrava

	Energy consumption of standard vehicle [kWh]	Energy consumption of articulated vehicle [kWh]	Relation between energy consumptions
January	1,81	2,47	1,36
February	1,69	2,29	1,36
March	1,49	2,13	1,43
April	1,53	2,35	1,54
May	1,36	2,11	1,56
June	1,32	1,87	1,42
July	1,24	1,96	1,58
August	1,26	2,02	1,6
September	1,32	1,86	1,41
October	1,38	1,95	1,41
November	1,57	2,27	1,45
December	2,02	2,35	1,16
Overall	1,5	2,14	1,42

Table 5.7. Comparison of minimal covering rate of transportation route for standard and articulated vehicle

Charging power	Minimal covering of transportation route	
	Standard vehicle	Articulated vehicle
70 kW	43%	50%
200 kW	26%	31%
250 kW	21%	26%

5.4. Simulation of the supply system

5.4.1. The Monte Carlo method

The Monte Carlo method is based on a continuous repetition of a statistical experiment by means of which the analysis of the object's state is made at randomly selected initial factors. The effect of this is a decomposition of an exit variable probability. A simulation model is based on the following initial data:

1) trolleybus timetables,

2) deviations in timetable realization which were highlighted on the basis of the research on public transport punctuality carried out by the Public Transport Authority (Zarząd Komunikacji Miejskiej) in Gdynia,

3) the trolleybus speed profile – a relationship between expected vehicle speed and location, traction characteristics of trolleybuses.

On the basis of timetables and deviations from their realization a probability histogram was produced indicating the number of vehicles operating simultaneously on the power supply section (Fig. 5.25).

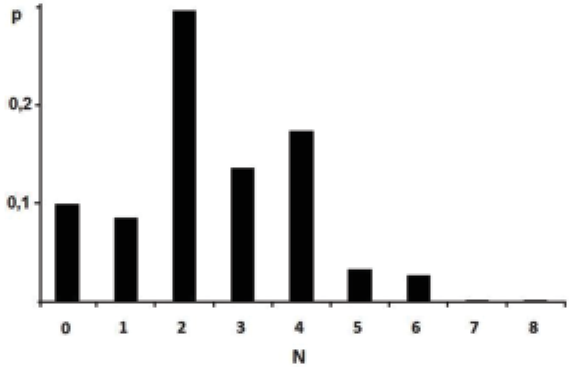

Fig. 5.25. An example of the histogram of a trolleybuses number *N* which are on the power supply section, *p* – probability

A number of vehicles being on the power supply section at the very moment is indicated on its basis.

The speed profile (Fig. 5.26) is the basis for indicating the layout of specific vehicles location probability along the power supply section (Fig. 5.27).

where: *k* – the coefficient of proportionality.

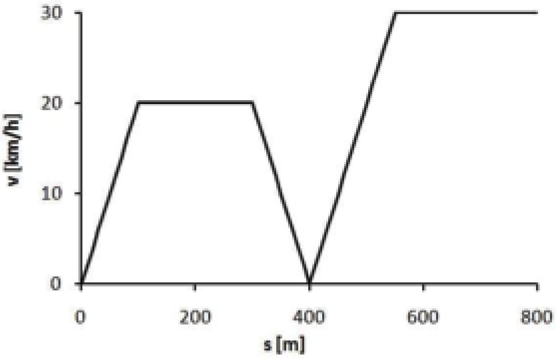

Fig. 5.26. An exemplary speed profile; s – the vehicle location, v - speed

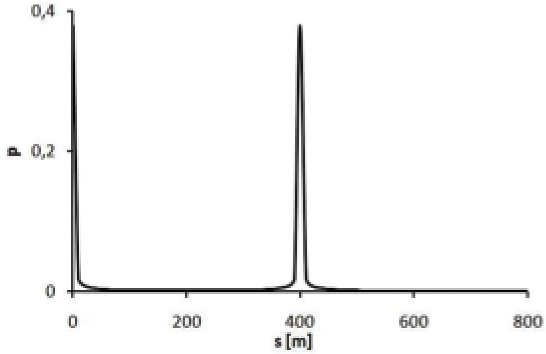

Fig. 5.27. A layout of the vehicles (s) location probability (p) for the speed profile from Fig. 5.25

Probability $P(s_1, s_2)$ to find the vehicle between points with coordinates s_1 and s_2 is proportional to the time of travel between these two points, which can be written:

$$P(s_1, s_2) = k \cdot \frac{s_2 - s_1}{v_{sr}} \tag{5.31}$$

where: v_{sr} - average speed on the road between points s_1 and s_2; k - coefficient of proportionality.

This probability is equal to the integral of the probability density $p(s)$:

$$P(s_1, s_2) = \int_{s_1}^{s_2} p(s)ds \tag{5.32}$$

marking the difference $s_2 - s_1$ as Δs we can write:

$$P(0, \Delta s) = k \cdot \frac{\Delta s}{v'_{sr}} = \int_0^{\Delta s} p(s)\, ds \qquad (5.33)$$

on $\Delta s \rightarrow 0$ this equation takes the form:

$$p(s) = k \cdot \frac{1}{v(s)'} \qquad (5.34)$$

which means that the density of the probability of finding a vehicle in a given point is inversely proportional to its speed.

A basic simulation cycle (Fig. 5.28) includes the following phases:

1) indicating the number of trolleybuses operating on the power supply section on the basis of timetables and deviations from their realization,

2) determining the location of specific vehicles on the basis of the vehicles location probability layout,

3) determining the currents absorbed from the traction network by specific vehicles,

4) calculating currents and voltage outflow in the power supply system.

This cycle is continuously repeated and as a result one acquires current and voltage probability layout in the power supply system.

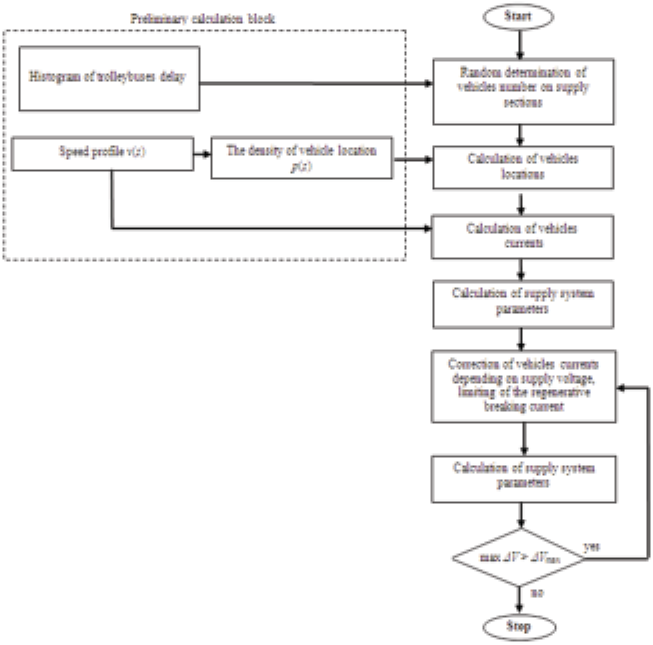

Fig. 5.28. A basic diagram of a simulation model

The current of specific trolleybuses is determined on the basis of the trolleybus speed and its derivative *dv/dt* in a defined place, i.e.:

1) if *dv/dt* > 0 – it means that a trolleybus is in the start-up phase and its current is defined on the basis of its characteristic,

2) if *dv/dt* < 0 - it means that a trolleybus is braking; in this situation one assumes the energy recovery to the network, the current value is defined basing on braking characteristic,

3) if *dv/dt* = 0 and *v* > 0 - it means that a trolleybus is going with a permanent speed. In real conditions (in practice) a permanent speed of the vehicle is acquired through a continuous pressing and releasing the drive pedal, in reference to which one may say about a quasi permanent speed. In this case a trolleybus current is indicated at random, on the basis of a probability layout acquired from a theoretical ride ,

4) if *dv/dt* = 0 and *v* = 0 - it means that a trolleybus is standing and its traction receivers current is zero.

To the currents indicated above one should add a trolleybus auxiliary receivers current, i.e. the current of its auxiliary systems and heating.

The state of regenerative braking is simulated in the following way:

1) in the first phase a trolleybus is treated as a current source of with a current value indicated on the basis of its traction characteristic,

2) if the value of voltage on receivers exceeds the permissible level of voltage for regenerative braking (in Gdynia it is 750 V), which means the lack of a possibility to receive generated energy, the vehicle is modeled as a voltage source of a voltage value adequate to permissible voltage for recuperation.

5.4.2. Example simulation of the power system

<u>Exemplary situation:</u> line with a length 10 km, with 20% covered by overhead wires (fig. 5.29), operated by single vehicles with charging power 250 kW in motion and 70 kW stationary. Nominal supply voltage 750 V. The analyzed traffic intervals are 2, 3 and 6 min.

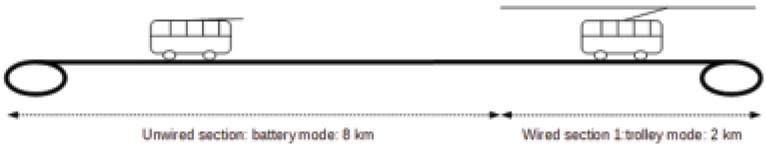

Fig. 5.29. A basic structure of an exemplary line

Based on the Monte Carlo simulation method, a model supply system analysis of a dynamic charging line was realized. The model system consists of a 2 km trolleybus line, on which operates dynamic charged electric buses. The line is divided into two supply sectors with length of 1 km each supplied from one traction substation. The basic parameters of the analyzed system are shown in table 5.8. It corresponds to an electric bus route with dynamic charging, where around 25% of the route is covered by catenary contact wires.

Table 5.8. Parameters of model dynamic charging system

The total length of route	8 km
The length of wired section	2 km
Type of vehicles	Standard, 2 axle, 12 meters
Supply voltage	750 V
Battery charging power	250 kW (move), 70 kW (stationary)
Internal voltage of substation	0,03 Ω

The four variants of supply of dynamic charging were analyzed:

1) standard trolleybus 2 direction catenary (wires in both directions connected in parallel) with contact wires measuring 100 mm^2 Cu (fig. 5.30),

2) trolleybus catenary with additional wire measuring 120 mm^2 Cu (fig 5.31),

3) standard trolleybus catenary with additional supply point placed at a distance of 640 m from the substation and connected by underground cable 2 x 630 mm^2 Al (fig. 5.32),

4) combination of variants 2 and 3: using additional wire measuring 120 mm^2 Cu and cable 2 x 630 mm^2 Al (fig. 5.33).

The simulations were generated for the operation of the transportation route with intervals of 2, 3 and 6 min. The main results are shown in tables 5.9 - 5.11.

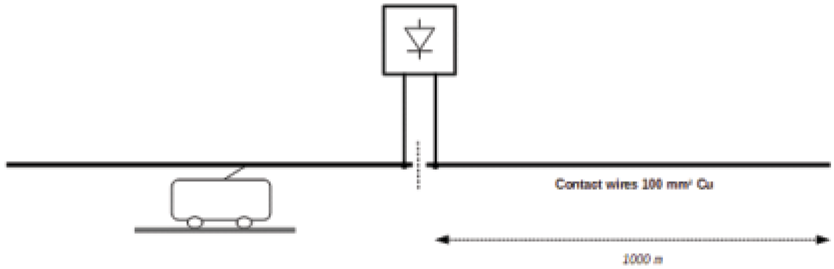

Fig. 5.30. A basic structure of supply system considered in simulation

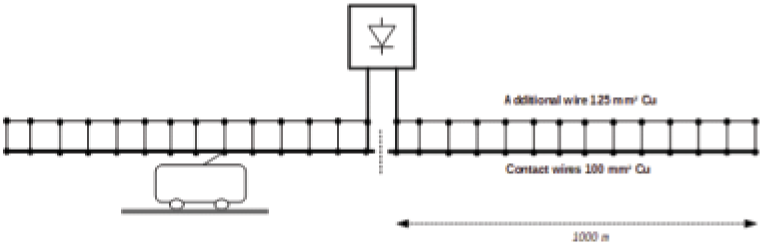

Fig. 5.31. A structure of supply system with additional overhead wire considered in simulation

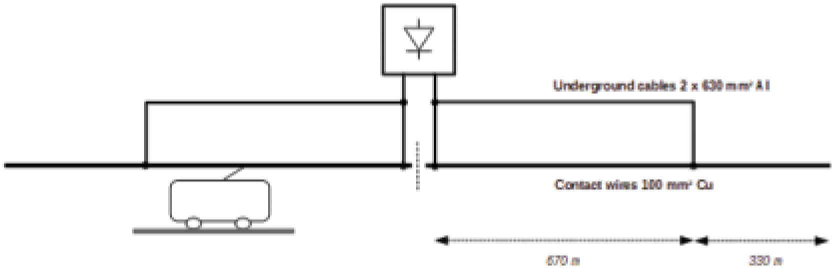

Fig. 5.32. A structure of supply system with additional underground cable considered in simulation

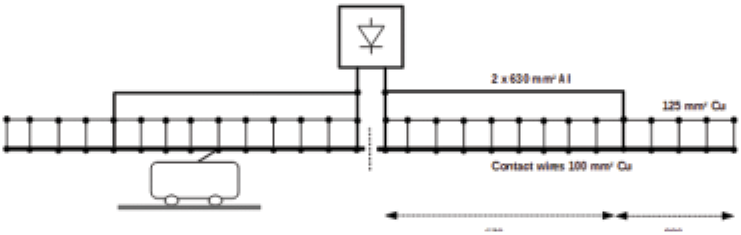

Figure. 5.33. A structure of supply system with additional overhead wire and underground cable considered in simulation

The control of the criterion for the proper functioning of short-circuit protection is one of the most important elements of the power system calculations, as this element determines both the operational safety and failure to protect in the situation where a short circuit can lead to serious damage, e.g. thermal damage of the traction network. The basic and most common short-circuit protection of the overhead contact line is DC overcurrent protection realized by a high speed circuit breaker. To ensure reliable switching of short circuits, the value of the DC circuit breaker activation - *the farthest from the substation* - should be smaller than the minimal short circuit current value I_{k_min} with safety factor k:

$$I_{cb} = k \cdot I_{k\_min} \tag{5.35}$$

Most often factor k is taken at the level of 0,8. The $I_{k\text{-}min}$ min value of the short-circuit current is determined as follows

$$I_{k\_min} = \frac{U_0}{R_{k\_max}} \qquad (5.36)$$

where U_o means substation voltage, R_{k_max} means the maximal resistance of short circuit (for the situation when the location of the short circuit is the farthest from the substation), which includes the internal resistance of the substation, the resistances of the DC supply cables and overhead wires resistance. In order to ensure the stability of the supply system work, the I_{cb} value short should be higher than the maximal value of the substation feeder load.

Table 5.9. Results of simulations for traffic interval 2 min

	Basic system	Extra Cu 120 mm2 wire	Extra 2 x Al 630 mm2 cables	Extra 2 x Al 630 mm2 cables + Cu 120 mm2 wire
Total power consumption [kW]	1665	1572	1517	1498
Transmission losses in DC supply system [%]	13,7	8,1	3,6	2,6
Average voltage on current collectors [V]	664	710	743	752
Minimal voltage on current collectors [V]	379	523	647	673
Average current of one supply section [A]	1009	953	919	908
Average number of vehicles on one supply section	3,3	3,3	3,3	3,3
Maximal short circuit resistance [Ω]	0,27	0,158	0,132	0,093
Minimal short circuit current [A]	2222	3797	4560	6454
Maximal feeder current [A]	2700	2700	2700	2700

Table 5.10. Results of simulations for traffic interval 3 min

	Basic system	Extra Cu 120 mm2 wire	Extra 2 x Al 630 mm2 cables	Extra 2 x Al 630 mm2 cables + Cu 120 mm2 wire
Total power consumpt. [kW]	1058	1014	982	976
Transmission losses in DC supply system [%]	10,3	6,0	2,9	2,0
Average voltage on current collectors [V]	708	742	767	772
Minimal voltage on current collectors [V]	366	616	676	703
Average current of one supply section [A]	641	614	595	591
Average number of vehicles on one supply section	2,2	2,2	2,2	2,2
Maximal short circuit resistance [Ω]	0,27	0,16	0,13	0,09
Min. short circuit current [A]	2222	3797	4559	6454
Maximal feeder current [A]	1935	1935	1935	1935

Table 5.11. Results of simulations for traffic interval 6 min

	Basic system	Extra Cu 120 mm2 wire	Extra 2 x Al 630 mm2 cables	Extra 2 x Al 630 mm2 cables + Cu 120 mm2 wire
Total power consumpt. [kW]	528	512	503	500
Transmission losses in DC supply system [%]	6,9	3,9	2,0	1,4
Average voltage on current collectors [V]	751	773	789	794
Minimal voltage on current collectors [V]	585	675	715	745
Average current of one supply section [A]	320	311	305	303
Average number of vehicles on one supply section	1,1	1,1	1,1	1,1
Maximal short circuit resistance [Ω]	0,27	0,16	0,13	0,09
Min. short circuit current [A]	2222	3797	4556	6454
Maximal feeder current [A]	1184	1184	1184	1184

5.4.3. Increasing energy demand where existing trolleybus infrastructure is used for the charging of dynamic charged buses

In many cases, there is a trolleybus infrastructure that can be used for charging vehicles. This allows for a significant reduction in infrastructure costs. However, it requires the analysis of the existing power supply system and its modernization may be necessary in some situations. When using existing trolleybus infrastructure for dynamic charging of electric buses, a significant increase in the load current should be expected. This is illustrated in figures 5.34 and 5.35.

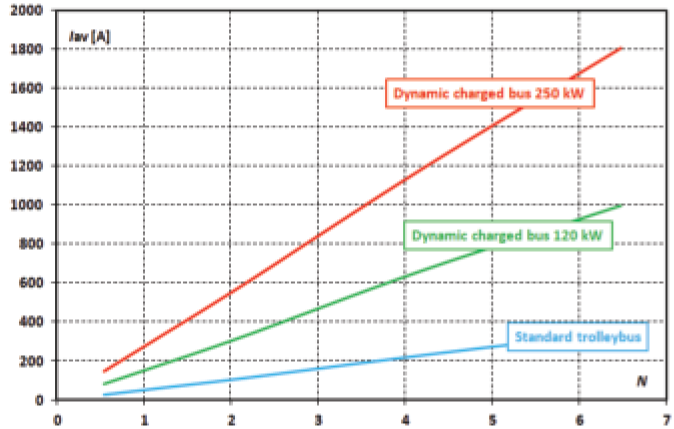

Fig. 5.34. The average value of supply section load in function of average number of vehicles for in the case of standard trolleybus and dynamic charged electric bus with charging power 120 kW and 250 kW

Calculations were also made for a vehicle with lower charging power. The highest load increase occurs in the case of the average load current. For vehicles charged with power of 250 kW the average power consumption could be more than 5 times greater than standard trolleybuses. However, as a benefit, the increase in the maximum load current is much smaller. Its value is 2,5 times higher in the case of a 250 kW charged ebus compared with a trolleybus. This is important because in practice, increased limitations on the trolleybus system power supply are related to the maximum load values in the most adverse traffic conditions rather than the average ones.

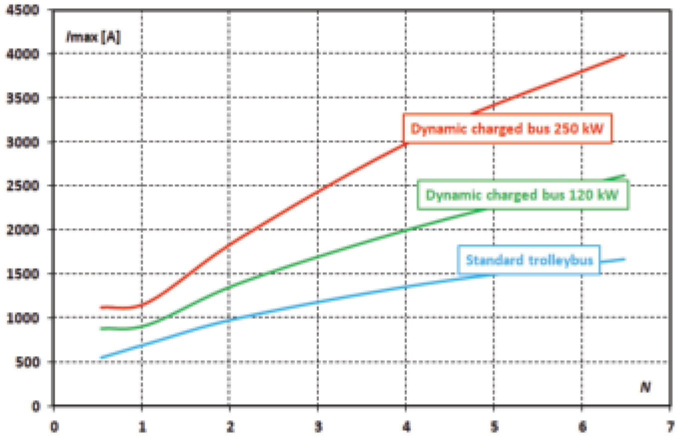

Fig. 5.35. The maximal value of supply section load in function of average number of vehicles for in the case of standard trolleybus and dynamic charged electric bus with charging power 120 kW and 250 kW

5.5. Traction battery capacitance

The cost of the traction battery is 30 to 50 percent of the purchase price of the electric bus. In addition, the operator must take into account this expense when replacing the battery after the end of its useful life. Coverage of part of route by trolley line enables the reduction of traction battery capacitance, which in turn reduces the cost of the vehicle. An exemplary analysis follows:

<u>Exemplary situation:</u> *line with a length of 10 km is operated by standard length electrical buses. Maximal energy consumption at the level 3 kWh/km is assumed.*

Three alternative systems of line electrification are analyzed 3 (fig. 5.36):

- operation by standard electrical bus with one charging station and Terminus 1. The charging power is 400 kW,
- operation by dynamic charged battery bus with one 3 km wired section (variant 1),
- operation by dynamic charged battery bus with two wired sections: 1 km and 2 km (variant 2).

The average charging power of the dynamic charging system is 140 kW, the average velocity in the wired section is 20 km/h. The minimal charge level is assumed to be at 50%. In table 5.12 the energy balances of the analyzed variants are shown. In the case of a standard battery bus the maximal discharge level is 60 kWh. With a minimal discharging rate of 50%, this requires a 120 kWh traction battery. In the first dynamic charged bus variant the battery is discharged with energy 42 kW, what provides the required battery capacitance of 84 kWh. In the second variant the battery is maximally discharged with power 15 kWh. As a result of that, a traction battery with capacitance of 30 kWh will be enough to fulfill transportation route conditions. The fig. 5.37 presents the graph of battery charge level of the analyzed variants. Covering only part of the transportation route allows for the reduction of the required traction battery capacitance. The capacitance reduction is greater where more than one wired section is used. This allows for operation in alternate modes; charging - discharging - charging - discharging. Thanks to this, the amount of discharge is significantly reduced.

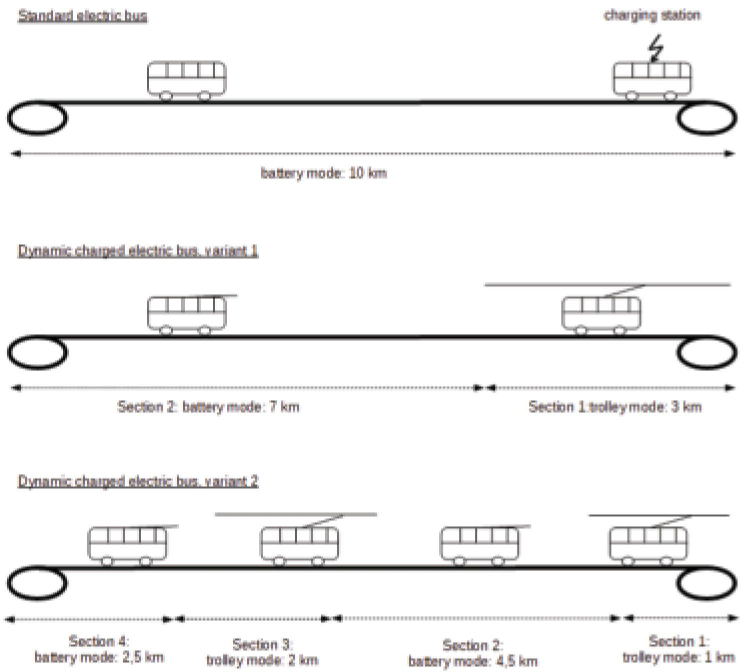

Fig. 5.36. The scheme of an example route operated by standard electrical bus and two variants of dynamic charged buses

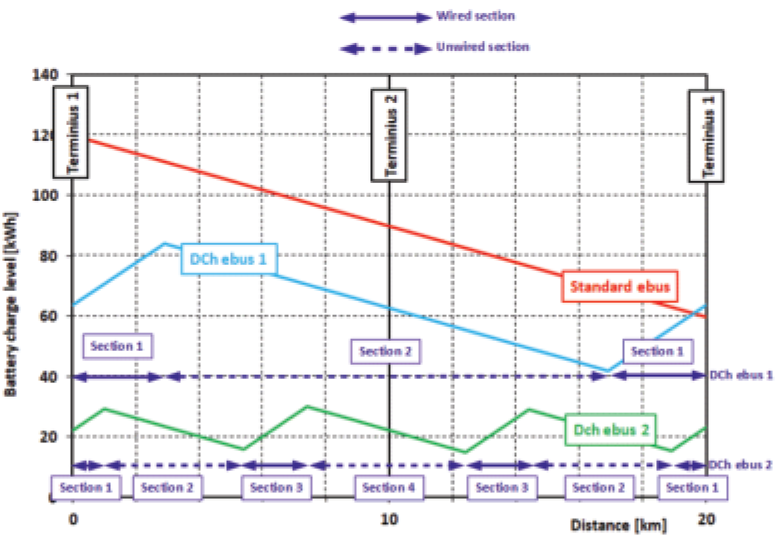

Fig. 5.37. Diagram of battery charge level during operation of route by standard electrical bus and two variants of dynamic charged buses

Due to the effects of traffic congestion, the energy consumption in peak hours (chapter 5.1.1, fig. 5.5) is greater than the average energy consumption for an entire day. The resulting methods of estimation of battery capacitance and charging power are:

1) The charging power can be set according the full day value, in this case the charging power may be insufficient in peak hours (increased energy consumption) to fully charge the batteries. As a result, the batteries will not be fully charged in some cases while running in wire mode. Therefore, it is necessary to increase the capacity of the battery should it be unable to fully charge it.

2) The charging power can be set according the maximal peak hours energy consumption value. This allows the batteries to be fully charged while running in wire mode, so a reserve battery capacitance is not required. On the other hand it is necessary to increase the power of the battery charger.

In another words it can be partly compared to high energy and high power battery systems in stationary charged electric buses.

Table 5.12. Energy balance of operation of route by standard electrical bus and two variants of dynamic charged buses, sign "+" sign means battery charging, "-" battery discharging

<table>
<tr><th rowspan="2"></th><th colspan="2" rowspan="2">Standard electric bus</th><th colspan="4">Dynamic charged electric bus</th></tr>
<tr><th colspan="2">Variant 1</th><th colspan="2">Variant 2</th></tr>
<tr><td rowspan="4">Direction 1</td><td>Terminius 1</td><td>+ 60 kWh
9 min</td><td rowspan="2">Section 1
wired: 3 km</td><td rowspan="2">+ 21 kWh</td><td>Section 1
wired: 1 km</td><td>+ 7 kWh</td></tr>
<tr><td rowspan="3">Route
10 km</td><td rowspan="3">- 30 kWh</td><td>Section 2
unwired:
4,5 km</td><td>- 13,5 kWh</td></tr>
<tr><td rowspan="2">Section 2
unwired: 7
km</td><td rowspan="2">- 21 kWh</td><td>Section 3
wired: 2 km</td><td>+ 14 kWh</td></tr>
<tr><td>Section 4
unwired:
2,5 km</td><td>- 7,5 kWh</td></tr>
<tr><td rowspan="4">Direction 2</td><td rowspan="3">Route
10 km</td><td rowspan="3">- 30 kWh</td><td rowspan="2">Section 2
wired: 7 km</td><td rowspan="2">- 21 kWh</td><td>Section 4
unwired:
2,5 km</td><td>- 7,5 kWh</td></tr>
<tr><td>Section 3
wired: 2 km</td><td>+ 14 kWh</td></tr>
<tr><td rowspan="2">Section 1
unwired: 3
km</td><td rowspan="2">+ 21 kWh</td><td>Section 2
unwired:
4,5 km</td><td>- 13,5 kWh</td></tr>
<tr><td>Terminius 1</td><td>0</td><td>Section 1
wired: 1 km</td><td>+ 7 kWh</td></tr>
</table>

Fig. 5.38 shows the graphical comparison of the above mentioned methods, where two charging solutions are compared. In the case of a charger with lower power (80 kW) the charging power is insufficient to fully charge the batteries and reserve capacitance is required. Greater charging power (150 kW) allows for the batteries to be fully charged in case of route disturbances (traffic congestion). An exemplary relationship between the charging power and the required battery capacity as a function of the autonomous driving distance (3, 8 and 18 km) for a coverage of 30% of the route is shown in the figure. It is based on an analysis of the trolleybus traffic in Gdynia, therefore it is indicative (fig. 5.39).

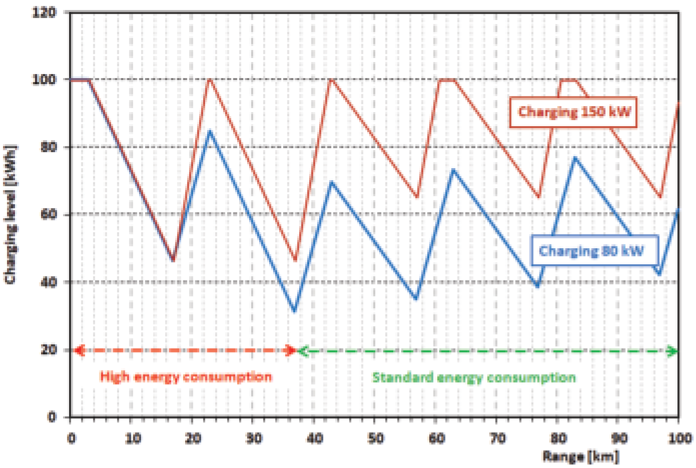

Fig. 5.38. The illustration of short period influence of energy consumption increasing in case of two values of charging power

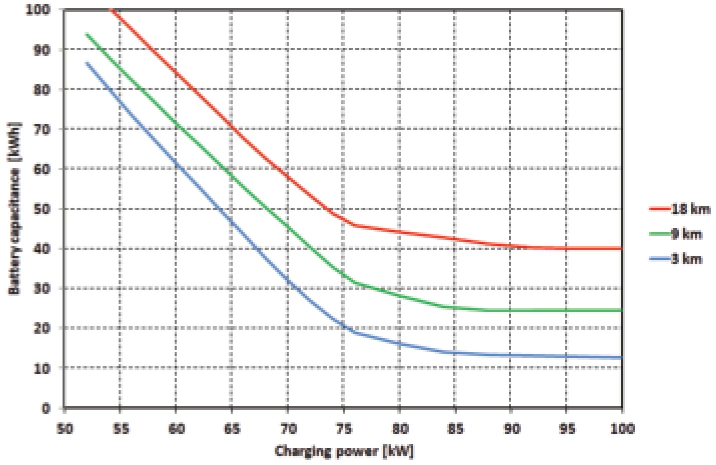

Fig. 5.39. The example of dependence between charging power and required battery capacitance for tree values of transportation route length

6. FINANCIAL ANALYSIS OF THE IMC SYSTEM

The biggest difference between stationary charged electrical buses and dynamic charged electrical buses from the economic point of view is the cost structures – with the latter having a higher level of fixed costs and a lower level of variable costs. Additionally, in the case of electric buses, a greater portion of the costs have a high degree of variability, i.e. risks related to the price of traction batteries. A decline in battery price can be expected, but the size of the reduction is very difficult to assess. Currently, the cost of the battery can be up to 50% of the vehicle price. Moreover, during the entire lifetime of the vehicle it will be necessary to replace the battery at least once. The cost of the driver is the second factor that differentiates the operating costs of both systems.

Stationary charging requires an increase in the number of vehicles servicing the transportation line due to the need to provide an adequate time reserve for vehicle charging. This results in an increase in the number of vehicles in service and the number of drivers. This additional cost is difficult to estimate due to the differing ways of organizing driver service in various transport systems, but currently the cost of drivers accounts for up to 50% of all maintenance costs of the transport system. Thus even a slight increase in the number of rolling stock can cause a significant increase in costs. For this reason, this factor can also be treated as a random element.

A financial analysis will be done – analysis of costs, including maintenance costs and costs of assets. A financial comparison of stationary charged electric buses and dynamic charged electric buses will be carried out on the basis of a discounted life cycle cost analysis - LCC. It shows total discounted costs (infrastructure and vehicl

$$FNPV = C_i + \sum_{n=1}^{n=T} \frac{C_{op}(n)}{(1+r)^n} - \frac{SV}{(1+r)^T} \quad (6.1)$$

where:

C_i - initial costs,

T - entire period of analysis,

n - given time periods (years),

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i - financial discount rate.

$C_{op}(n)$ - operational costs in a given period n (year),

SV - residual value of infrastructure and vehicles after period T of analysis.

The investment and operational costs are shown in table 6.1. The cost of battery is the most uncertain element influencing the life cycle costs of transportation systems. The actual price of battery storage systems can be estimated at level 1 000 euro / kWh [32]. In 2017 a 25% reduction in battery price was observed. If this trend continues, the price of battery systems may decrease several more times. On the other hand, many experts are of a different opinion [32]. For this reason, the risk analysis assumes a drop in the price of the battery to 25% of the present value in the optimistic variant and maintenance of the current prices in the pessimistic scenario. Due to the lack of experiences in the field of battery systems lifespans, one and two battery changes were assumed during the lifetime of the vehicle.

In the case of static charged electric buses there is a need to ensure a guaranteed charging time at end points. This increases the required number of vehicles and the number of drivers. This charging time is influenced by random road congestion conditions and the organization of work by individual transport operators. For this reason, it should also be considered as a random factor. The maximum increase in the number of vehicles due to charging time $k_{charging}$ can be expressed as:

$$k_{charging} = \frac{2 \cdot T_r + T_{charg}}{2 \cdot T_r + T_{res}} \tag{6.2}$$

where:

- T_r - driving time in one direction,

- T_r - required charging time,

- T_{res} - time of minimal break at final stop.

The minimal value of $k_{charging}$ is 1, which means no need to ensure additional charging time. Charging station is localized on the one terminus. The scheme of dependence between several sources of financial risk related to electric buses is shown oh fig. 6.1.

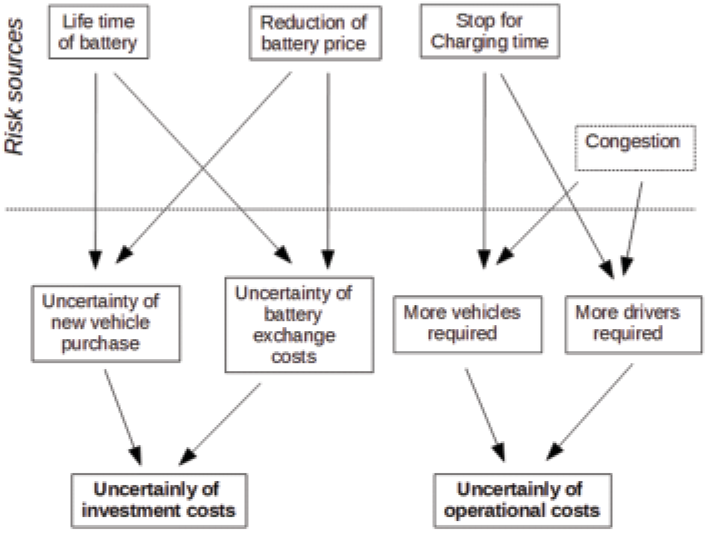

Fig. 6.1. Dependence between several sources of financial risk related to electric buses.

The calculations were made with the following additional assumptions:

- share of rides in peak hour is set at 25%, which is used to estimate the number of vehicles needed to serve the connection [32], lower share of rides in peak hour means that less vehicles are needed to serve the line, which influences total costs; share of rides in peak hour is defined as relative to the increasing frequency of transportation in peak hours in comparison to average all day frequency;
- 3 rush hours per day were assumed;
- number of workday equivalents per year is set at 310 [32], which equals 255 workdays and 110 non-workdays, with 50% daily supply of workdays;
- rolling stocks reserve at 10%.

The influence of battery cost reduction is presented in fig. 6.2 - 6.3. The calculations were made with an assumption of the same vehicle price for standard electric bus and dynamic charged electric bus 1 800 000 PLN. Figures 6.4 - 6.7 present life costs analysis and risk value of life costs for different coverage rates by catenary and different traffic intervals. Calculations were made with assumptions presented in table 6.1. It should be summed up that the investment in the traction network allows to reduce risk related to operating costs. This benefit is particularly visible in the high frequency of running vehicles.

Table 6.1. The investment and operationl cost of electric buses (C - certain cost, U - urceitain cost, HU - highly urceitain cost, S - static charged bus, D - Dynamic charged bus)

		Type of costs	Applicable for	Value, min. and max. values	Annotation
Investment costs	Vehicle purchase	U	S, D	Standard electric bus: 300 - 500 k EUR DChar Bus, variant 1: 350 - 550 k EUR DChar Bus, variant 2: 325 - 525 k EUR	- max. price: actual results of tenders and market analysis - min. price: assumption 75% reducing of battery price [32]
	Traction substation	C	D	300 k EUR	actual results of tenders [32]
	Overhead cathenary	C	D	300 k EUR/km	actual results of tenders [32]
	Charging station	C	S	300 EUR	technical analysis [32]
Operational costs	Drivers personal costs	U	S, D	0,7 EUR/km	[19, 32]
	Battery exchange costs	HU	S, D	Standard electric bus: 35 - 150 k EUR DChar Bus, variant 1: 25 - 100 k EUR DChar Bus, variant 2: 10 - 40 k EUR	- max. price: assumpted pride 1 k euro /kWh - min. price assumption 75% reducing of battery price [32] - the calculation were made for two variants: battery exchange one time and twice per vehicle lifetime
	Vehicle maintenance cost	U	S, D	0,30 EUR/km	[32]
	Overhead cathenary maintenance cost	C	D	25 k EUR/km	[32]
	Energy	C	S, D	0,08 EUR/kWh	[32]

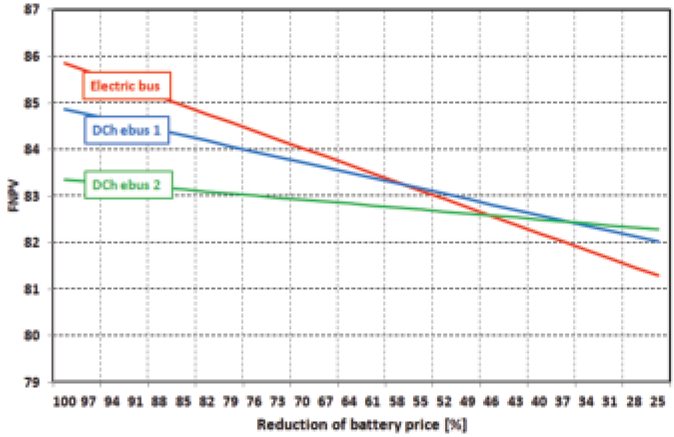

Fig. 6.2. Influence of the battery price reduction on life cycle cost (mln PLN) with assumption of one exchange of battery and transportation route interval 8 min and covering rate 30%

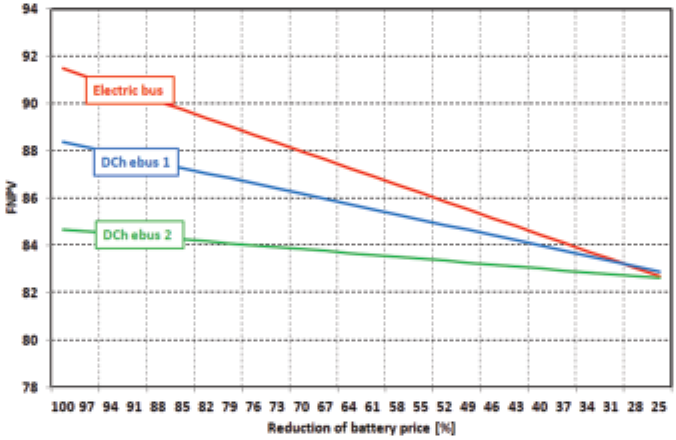

Fig. 6.3. Influence of the battery price reduction on life cycle cost (mln PLN) with assumption of one exchange of battery and transportation route interval 4 min

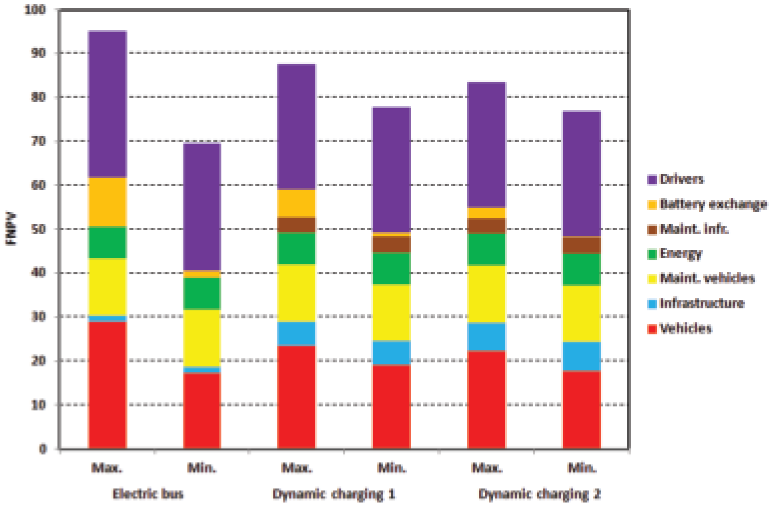

Fig. 6.4. Life cost analysis with assumption of 30% coverage of transportation route by overhead wires (in case of dynamic charging) and transportation route interval 8 min

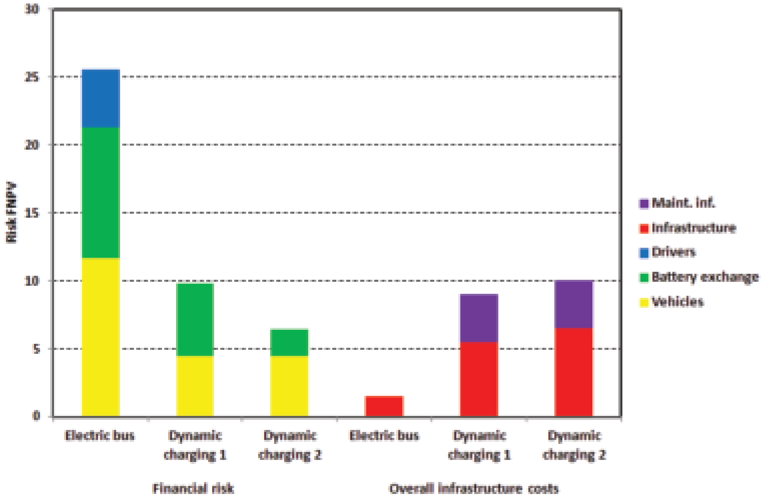

Fig. 6.5. Analysis of life cost risk (mln PLN) with assumption of 30% coverage of transportation route by overhead wires (in case of dynamic charging) and transportation route interval 8 min

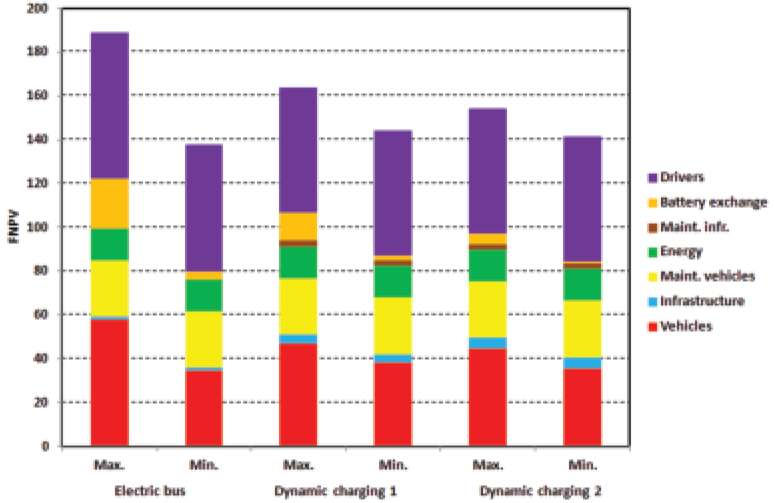

Fig. 6.6. Life cost analysis (mln PLN) with assumption of 20% coverage of transportation route by overhead wires (in case of dynamic charging) and transportation route interval 4 min

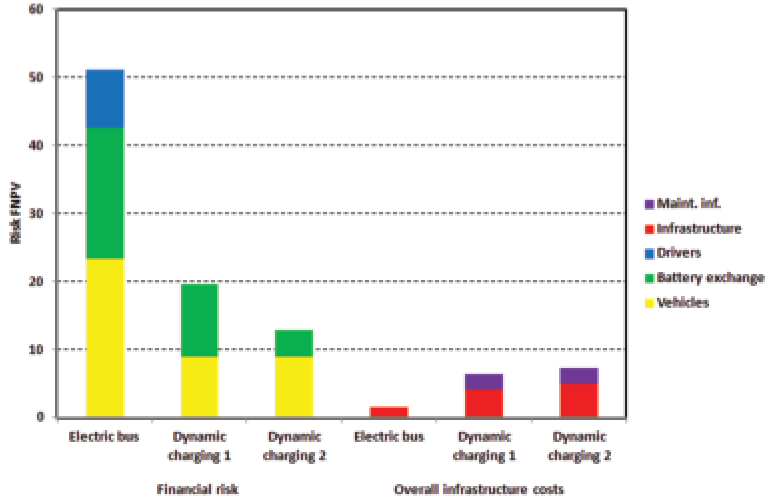

Fig. 6.7. Analysis of life cost risk (mln PLN) with assumption of 20% coverage of transportation route by overhead wires (in case of dynamic charging) and transportation route interval 4 min

7. POSSIBILITY OF IMPLEMENTATION OF DYNAMIC CHARGING

In many cities, there is already a trolleybus infrastructure that may be used as the basis for a dynamic charging system. The trolleybus network in Gdynia presents an example of the possibility of replacing bus lines with electric vehicles in the context of dynamic charging. In Gdynia the majority (70%) of public transportation is realized by buses. Trolleybuses cover 30% of the transportation work. Nevertheless, most of the bus routes are, in some part, operated under the existing trolleybus network. This trolleybus infrastructure can be used for dynamic charging of electrical buses thereby replacing diesel buses. Figure 7.1. shows the degree of coverage of several bus routes by the existing trolleybus catenary.

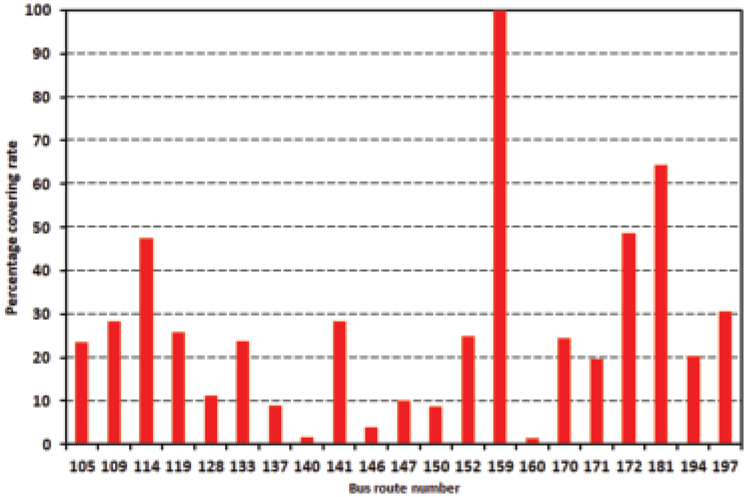

Fig. 7.1. The rate of covering of several bus routes by the existing trolleybus network in Gdynia

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In terms of operating the transportation route by dynamic charging buses, 20 - 35% of the route should be covered by overhead wires. The coverage value is not explicitly determined and depends on several parameters. Technical progress allows the reduction of this value. It was determined how much of the transportation work can be realized by dynamic charging buses in function of the minimal coverage rate. The results are shown on fig. 7.2.

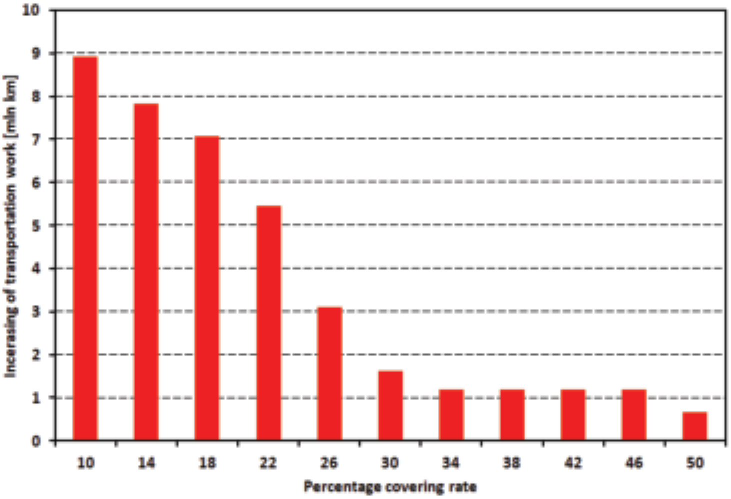

Fig. 7.2. Potential of increasing of transportation work by implementation of dynamic charging on the basing of existing trolleybus infrastructure in Gdynia in function reqired route covering rate

Slight extensions to existing trolleybus networks would allow for a significant increase in the possibility of dynamic charging. This possibility can be seen in the example of Gdynia. Fig. 7.3 presents the existing trolleybus network with 3 proposed extensions: Sections I, II and III. The length of each extension is around 2 km. Fig. 7.4 shows the coverage rate of several bus lines after realization of the extensions. Consequently, fig. 7.5 shows the possible increase of transportation work. The presented values are related to the actual transportation work of the bus routes (only the bus routes which are located under the existing trolleybus network are taken into account).

Fig. 7.3. The possibilities (red lines) of extenxions of existing (black line) trolleybus network in Gdynia

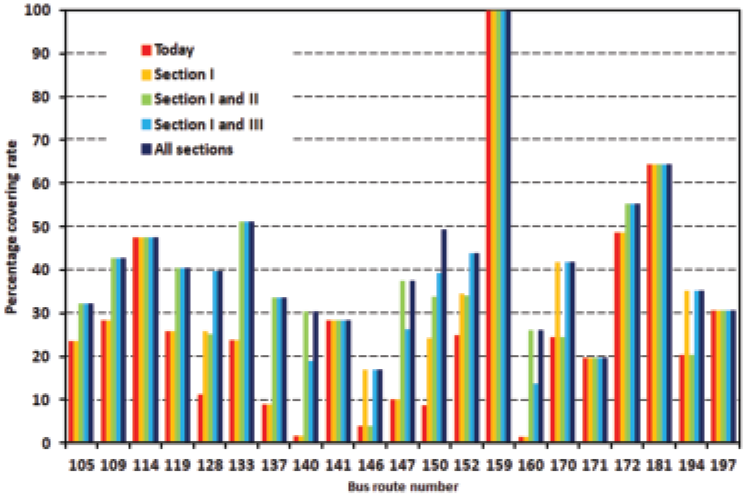

Fig. 7.4. The rate of covering of several bus routes by cathenary in case of exteni on the existing trolleybus network in Gdynia

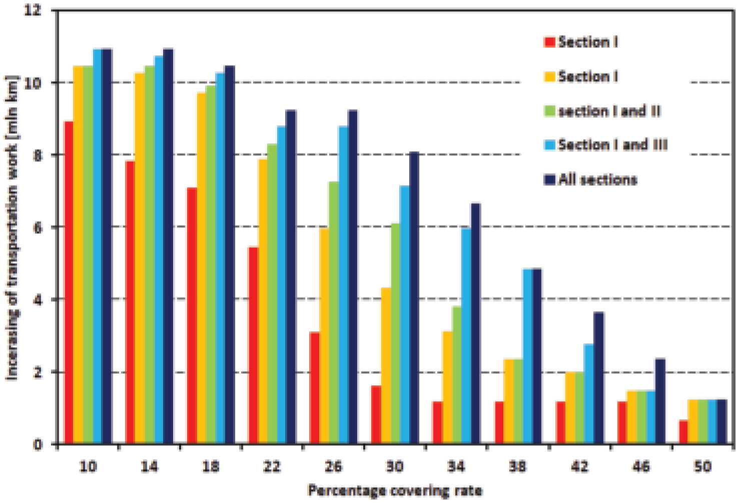

Fig. 7.5. Potential of increasing of transportation work by implementation of dynamic charging on the basing of existing trolleybus infrastructure in Gdynia in function required route covering rate for several variants of trolleybus network extension

8. FINAL REQUIREMENTS AND CONCLUSIONS

The study analyzed the minimum requirements for the dynamic system of charging depending on different external parameters. Analysis was carried out based on limiting technical criteria, maximal values of energy consumption, statistical analysis of energy consumption data and estimation of data from traction batteries. The comparison of the results is shown in table 8.1. The graphical presentation is shown on fig. 8.1. Due to the random nature of energy consumption and traffic conditions, the results obtained differ from each other. Nevertheless, several groups of results are visible along with the regularities resulting from them. With currently used vehicles, the minimum degree of coverage with the traction network is at a level of 40% - 50%. This value can be reduced by increasing charging power to 25%. In the case of a supply system of 750 V DC it is possible to decrease this rate to 20%. In the case of a reduction in the heating power of the vehicle or use of heating sources other than electric, it is possible to reduce the degree of coverage below 20%. Fig. 8.2 shows an estimation of the minimal coverage rate in function of charging power, based on (8.4), the energy consumption for a standard vehicle was assumed to be 1,5 kWh/h (summer) and 3 kWh/km (winter) and, correspondingly for an articulated vehicle, 1,95 kWh/km and 3,9 kWh/km. This confirms the previously calculated requirements for a dynamic charging system.

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Table 8.1. The comparison of several requirements for rate of minimal coverage of route by traction overhead wires (P_{ch_m} - charging power while moving, P_{ch_z} - charging power while stopping, if not mentioned supply voltage is 600 V)

	Conditions	Charging condition	Minimal covering rate
Calculation based on energy consumption registrations - limit parameters from a technical point of view - limitation of current collector	Summer time, standard vehicle (chapter 5.1.2)	P_{ch_m}=275 kW P_{ch_z}=85 kW U=750 V	16%
	Winter time, standard vehicle (chapter 5.1.2)	P_{ch_m}=255 kW P_{ch_z}=55 kW U=750 V	19%
	Summer time, standard vehicle (chapter 5.1.2)	P_{ch_m}=220 kW P_{ch_z}=70 kW	20%
	Winter time, standard vehicle (chapter 5.1.2)	P_{ch_m}=200 kW P_{ch_z}=60 kW	23%
Calculation based on energy consumption registrations, statistic analysis for annual energy consumption	Standard vehicle (chapter 5.2)	P_{ch_m}=70 kW P_{ch_z}=70 kW	40%
	Standard vehicle (chapter 5.2)	P_{ch_m}=200 kW P_{ch_z}=70 kW	25%
	Standard vehicle (chapter 5.2)	P_{ch_m}=250 kW P_{ch_z}=100 kW U=750 V	20%
	Articulated vehicle (chapter 5.3.4)	P_{ch_m}=70 kW P_{ch_z}=70 kW	50%
	Articulated vehicle (chapter 5.3.4)	P_{ch_m}=200 kW P_{ch_z}=70 kW	31%
	Articulated vehicle (chapter 5.3.4)	P_{ch_m}=250 kW P_{ch_z}=100 kW U=750 V	26%
Estimation based on registrations of battery operation	Summer time, standard vehicle (chapter 5.3.3)	P_{ch_m}=70 kW P_{ch_z}=70 kW	32%
	Winter time, standard vehicle (chapter 5.3.3)	P_{ch_m}=70 kW P_{ch_z}=70 kW	53%
	Summer time, standard vehicle (chapter 5.3.3)	P_{ch_m}=200 kW P_{ch_z}=70 kW	17%
	Sinter time, standard vehicle (chapter 5.3.3)	P_{ch_m}=200 kW P_{ch_z}=70 kW	25%

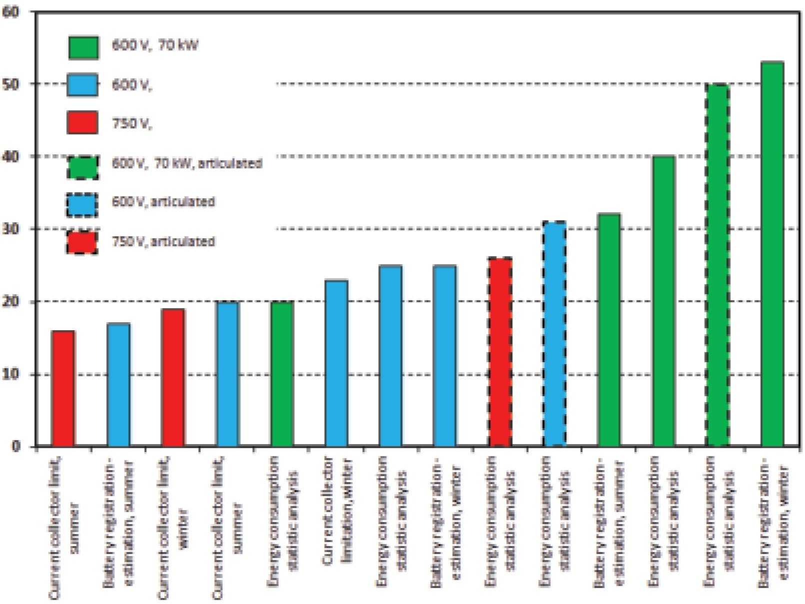

Fig. 8.1. Summary of minimum catenary coverage for various operational conditions and charging conditions.

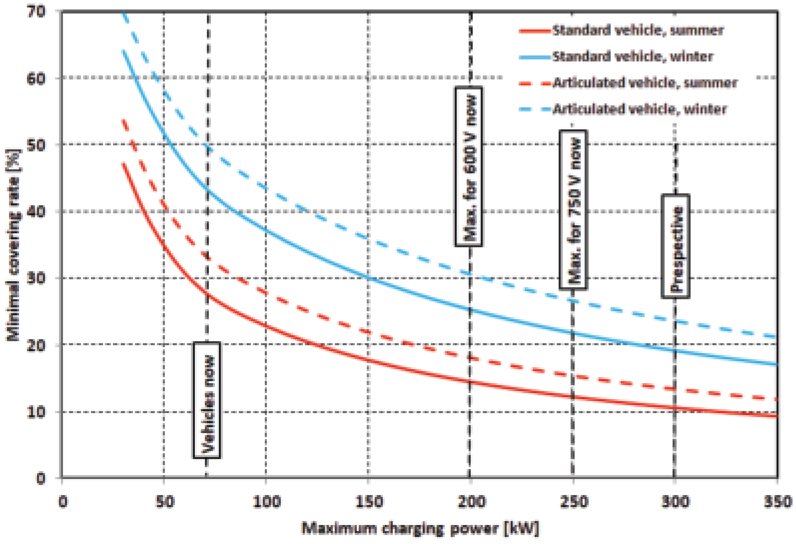

Fig. 8.2. Minimum catenary coverage in function of maximal charging power

The following factors allowing for the further development of dynamic charging systems can already be defined:

-improvement of current capacity of the collector, an increase from 500 A to 800 A is expected,

- improvement of charging converted, mainly through new semiconductor technologies (SiC),

- reduction of the energy consumption of auxiliaries (heat pump, intelligent management).

These treatments will allow for further improvement of the system. It can be summed up that the way forward for the development of dynamic charging systems is open.

Despite the fact that the number of cities exploiting electric buses in urban transport is increasing, the existing systems are test systems, and there is still no agreement among the users with regard to an optimal and universal solution for electric buses. The issue of charging is one of the biggest problems. On the other hand, trolleybus transport in numerous cities is considered to be outdated. Dynamic charging makes it possible to combine the advantages of trolleybuses and electric buses.

Dynamic charging requires that only 20%-30% of the route be electrified. What is more, in the case of common sections on many public transport routes, there is a possibility that the overhead contact line may be used by vehicles operating on a number of routes. This solution is particularly suitable for existing trolleybus networks and allows for more effective utilisation of the infrastructure. Moreover, in many cases it may be justifiable to construct brand new public transport systems based on the IMC, particularly in connection with the use of dedicated traffic lanes for buses.

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