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Hybrid Energy Storage Devices for Rapid Charge Stations of Electric Vehicles

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Abstract*: Insufficient development of infrastructure of electric vehicles is one of major constraining factors in attempts to their wider application. The main bottleneck is the development of extensive network of charging stations aiming at practical and economically reasonable operation of electric vehicles similar to that for conventional vehicles with internal combustion engines. Most activities devoted to adaptation of existing or development of new infrastructure facilities are related with the necessity to borrow significant funds for capital construction which has detrimental effect on their investment attraction. This promotes searching for alternative solutions including those related with the use of existing infrastructure vehicle facilities and electrical networks. This work discusses integration of fast charge stations into low intensive power supply system of petrol filling stations by means of hybrid energy storage devices based on lithium-ion batteries and supercapacitors. The flowchart of hybrid energy storage device and general principles of its operation are described in details.

***Index Terms*: hybrid energy storage, lithium-ion batteries, supercapacitors, ultracapacitors, electric vehicle, fast charging station, petrol station**

I. INTRODUCTION

One of the most progressing trends in global automobile industry is electrification of vehicles. According to estimations of International Energy Agency (IEA), in 2015 the threshold of 1 million vehicles with high degree of electrification (PHEV and BEV) on public highways was exceeded (Fig. 1).

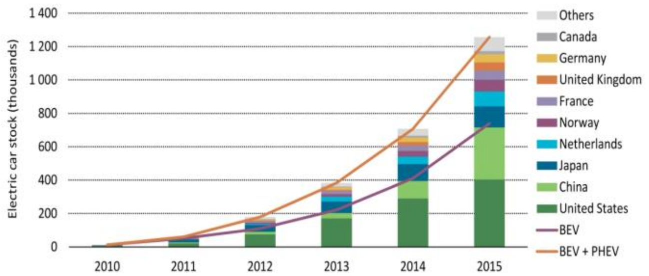

Fig. 1. Development of global fleet of electric vehicles.

It should be mentioned that the intensive growth of this segment of automobile market took place in 2010 which was stipulated by advances in technologies and state regulations in the field of automobile transport. Until that time, only several hundreds of such vehicles existed [1].

According to the FEV GmbH forecast concerning electrification degree of automobile market, in the nearest decade the fleet of such vehicles will increase significantly, including HEV, PHEV and BEV (EV). As exemplified by European market (Fig. 2), this market segment could be as high as about 3 million automobiles to 2020 and above 7 million automobiles to 2025 [2].

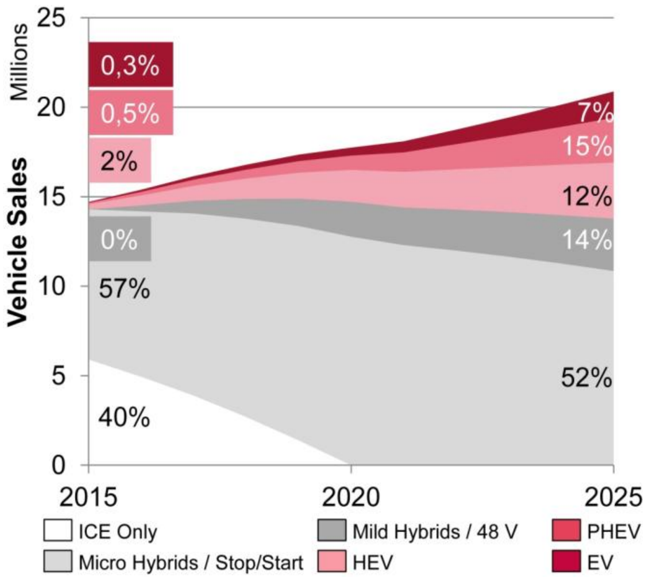

Fig. 2. Forecast of European automobile market in terms of electrification degree.

Despite the fact that the main markets of electric vehicles, especially BEV, are the US and China markets, positive trends are observed also in the Russian automobile market. According to the data by Avtostat analytical agency, early in 2016, 647 electric vehicles were registered in Russia, early in 2017 – 920 electric vehicles, and in January, 2018 – already 1771 electric vehicles. These data confirm the increased demand for such vehicles. To be fair, it should be mentioned that the main portion of electric vehicles is concentrated in the Moscow region, Primorsky region, Khabarovsk region, and Krasnodar region.

The main constraining factors of wide use of electric vehicles in Russia are as follows:

- high price of electric vehicles stipulated by the cost of batteries;
- low liquidity of electric vehicles in secondary market related with limited resource of batteries and costs of their replacement;

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- relatively low driving distance of electric vehicle with one charge, especially at negative ambient temperatures, restricted by the applied methods of energy accumulation;
- poorly developed infrastructure, especially that of charge stations.

If the first three factors are stipulated exclusively by technological constraints with respect to development of efficient, high capacity and available energy storage devices, then the latter is related mainly with necessity of high investments to infrastructure development. Therefore, its profitability in the nearest future is not obvious due to low portion of electric vehicles in Russia as well as due to difficulties of overcoming administrative barriers while developing infrastructure facilities.

At present, development of charge infrastructure of electric vehicles is an urgent issue, the leaders in this industry are China, USA, Japan, and some European countries. In Russia, this trend is at the very beginning, thus, about several hundreds of charge stations exist in Russia, while their major portion is in European part of the country. Figure 3 shows comparison diagrams with the ratio of the electric charge stations to the petrol filling stations at the end of 2016 in some countries.

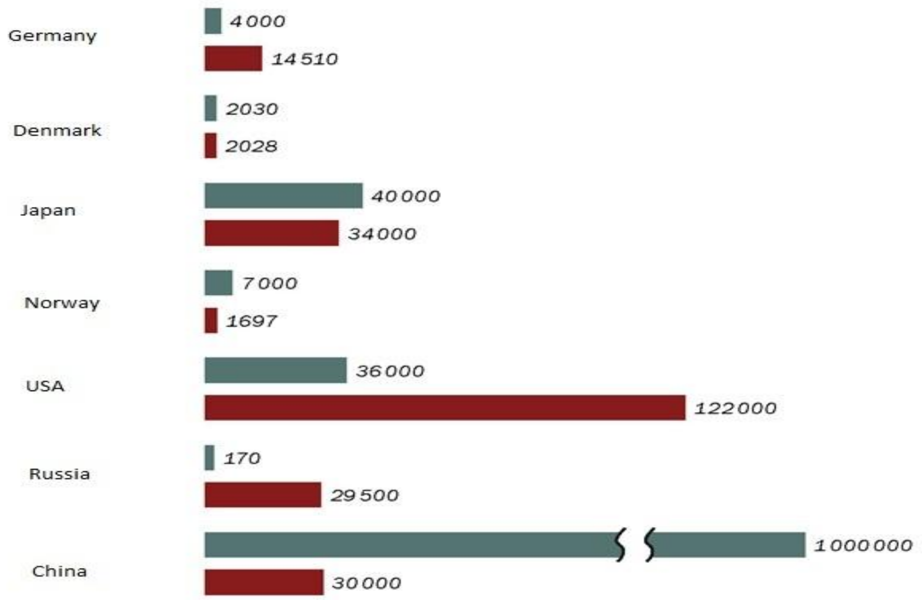

Fig. 3. Existing charge stations for electric vehicles and petrol filling stations [3] in 2016 (grey color: charge stations; red color: petrol filling stations).

Figure 4 shows diagram of global statistics of increase in charge stations for electric vehicles and plug-in hybrids from 2010 to 2015 [1], which confirms positive trend of annual increase in the number of charging stations, especially with respect to private and slow charge public stations.

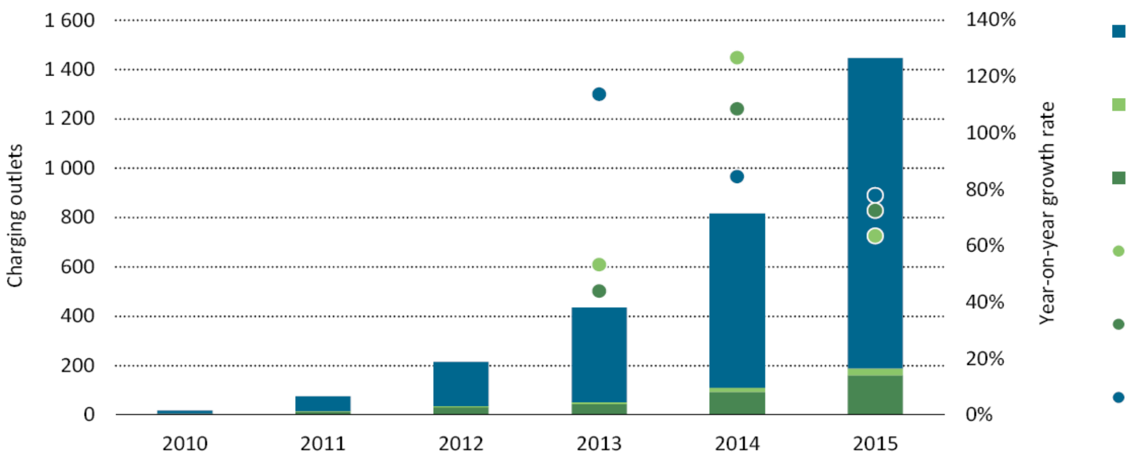

Fig. 4. Increase in the number of charge stations for electric vehicles and plug-in hybrids.

The presented data demonstrate peculiar feature of modern charge infrastructure in private sector: most charge stations are deployed at office parking lots for charging batteries during the daytime and in private households for charging during the nights using domestic networks for slow charging. All existing networks of charge stations are based on this principle.

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Herewith, it should be mentioned that obligations on arrangement of charging infrastructure in private households are specified legally in some counties. For instance, in the European Union the law is adopted according to which each new house erected after 2019 should be equipped with charge stations for electric vehicles.

Unfortunately, taking into account the Russian reality, such approach to arrangement of charging infrastructure in Russia cannot be implemented which can be attributed to predominant position of multi-unit apartment buildings at real estate market, and their infrastructure cannot provide high capacity energy and individual parking place for everyone. In its turn, this should promote searching for alternative approaches to creation and development of charge stations. It should be taken into account that an important condition upon arrangement of charging infrastructure is elimination of difference between electric vehicle and conventional vehicle with regard to usability and simplicity of charging. Only in this case it is possible to expect positive response from customers characterized by growth of fleet of electric vehicles and, as a consequence, stable demand for electric power provided by charge stations. This condition can be met by active implementation of fast charge stations accompanied by supply of high capacity electric energy.

II. METHODS

It is obvious that creation of well-developed charging system from scratch including fast charge stations in Russia is too expensive under conditions of restricted demand and is absolutely unprofitable. Even in the case of high investments the cost of energy in general charge system for customer will be unreasonably high due to low demand which can be attributed to intention of investors to reimburse their expenses. Thus, it would be more reasonable to apply global experience and technical solutions in this field to existing power generating facilities and electric networks.

A possible variant of usage of existing municipal energy facilities is the arrangement of charging sites in the vicinity of existing power stations. The point is that during several decades the municipal transport established infrastructure for development of network of charge stations. For instance, power stations in Moscow are located at every 5–7 km, previously they were aimed at traffic of trams and trolleybuses. Therefore, it is possible to arrange extensive charging system for electric vehicles which already do not use overhead wires. This relates not only to public but also to commercial and private transport. Every power station in its essence is the basis for charging unit which can be accompanied by multilevel parking lots [4].

Another variant of usage of existing electric networks which depends less on location of major municipal energy generating facilities and energy distribution units is deployment of charge stations at existing petrol filling stations. It should be mentioned that such approach is supported by the Russian government and the relevant issues were discussed already in 2017 concerning deployment of charge stations at conventional filling stations and parking lots as well as at shopping and entertainment centers [5]. Investments from private companies could be attracted, for instance, by bonuses for electric energy consumed by petrol filling stations. The owners of petrol filling stations with installed electric charge stations as well as the owners of other charging infrastructure could pay for electric energy according to bonus tariffs. As highlighted in the governmental strategy of development of automobile industry up to the year 2025, either discount or zero tariff for electric energy will be granted [6].

However, despite seeming obviousness of integration of electric charge stations into existing infrastructure of petrol filling stations, implementation of this strategy is accompanied by certain difficulties. In order to install fast charging stations at petrol filling stations, it is required to provide higher power than that existing at filling stations. Taking into account that the capacity of electric network at any average filling station is about 50 kW, including up 35...40 kW for own needs (fuel storage and supply, lighting, heating, and etc.), it would be unreasonable to connect additional power consumer in the form of fast charge station, its capacity can be from 50 to 100 kW; additional labor intensive and expensive modifications of network layout are required as well as connection of filling station to new high capacity network. According to expert appraisals, the cost of one charging complex can be as high as several million rubles depending on type of charging unit, and the major portion is comprised of capital expenses for construction and retrofitting of existing energy system of petrol filling stations [7].

One of the most efficient and reasonable methods of integration of modern fast charge stations into energy system of existing petrol filling stations is implementation of energy storage device into charging complex which will serve as a buffer accumulating energy during period of low demand and providing it during charging. Such approach to arrangement of charging procedure at existing filling stations is accompanied by certain requirements to design of energy storage device, they are mainly directed at steady operation of charging complex with minimum costs of electric energy, such as:

- design of energy storage device should provide possibility of combined operation with fast charge stations;
- energy storage capacitance should provide possibility of uninterrupted charging during peak loads with consideration for possible use of free capacity of existing network of petrol filling station;
- lifetime of components and equipment of the energy storage device should be significantly higher than the reimbursement period of its implementation and operation at petrol filling station;
- design of energy storage device should provide possibility of its operation as emergency power supply for petrol filling station.

The aforementioned requirements can be completely satisfied by hybrid energy storage systems (HESS) based on lithium-ion batteries and supercapacitors. Battery pack and supercapacitor unit can be charged and discharged from AC network of general purposes via invertor which does not require for maximum capacity of charge station. The HESS can be charged during the times of bonus tariffs for electricity (during the nights), and when an electric vehicle arrives at the charge station and the cost of network energy is high (peak hours), then the energy stored in battery pack can be used for charging without network energy consumption via charging port combined with charging device for electric vehicle and providing maximum charging capacity in order to reduce charging time. If the energy stored in battery pack is insufficient, for instance, during simultaneous charging of several electric vehicles with cumulative variables exceeding capabilities of HESS, then the system provides simultaneous supply to these vehicles from battery pack and network. Upon abnormal situations related with power supply deactivation, HESS by means of additional automated system can operate as emergency power supply for short time operation of filling station in normal mode up to failure recovery. It should be mentioned that combined usage of lithium-ion batteries and supercapacitors increases lifetime of the batteries (up to 2...5 times) due to equalization of peaks of power consumption and charge by means of capacitance of supercapacitors.

Nowadays some Western companies (Tesla, Proterra Inc, Freewire Technologies, ABB and others) intensively implement technical solutions related with the use of energy storage devices in charging infrastructure of electric vehicles at various facilities, including petrol filling stations, however, in Russia these technologies are still at the very beginning.

III. DESIGN

On the basis of experimental results [8–11], the flowchart of HESS was developed with lithium-ion batteries and supercapacitors (see Fig. 5) adapted for operation in charging facilities for electric vehicles and for possible integration in infrastructure of petrol filling stations.

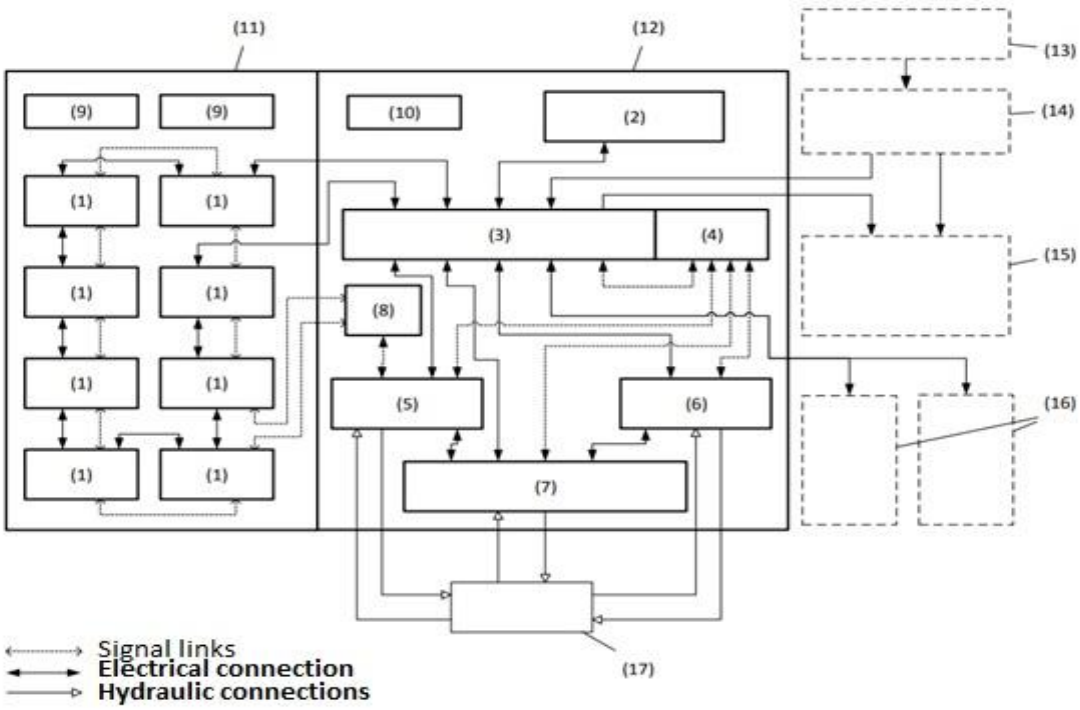

Fig. 5. Flowchart of HESS for charging electric vehicles at petrol filling stations.

HESS for fast charge stations is comprised of the compartment of batteries (11) where the battery packs (1) and the cooling fans (9) are located, and the compartment of supercapacitors and power electronics (12) comprised of one switching unit (3), one bidirectional power invertor (7), the supercapacitor unit (2), one voltage converter of battery pack (5), one voltage converter of supercapacitor unit (6), the control panel (4), the unit of battery charge monitoring and control (8), and the cooling fan (10). Semiconductor switches of the bidirectional invertor, voltage converters of battery pack and supercapacitor unit (not shown in the flowchart) are mounted on cooling plates which are connected to the fluid cooling circuit (17).

The voltage converters (5, 6) are intended for provision of the required levels of direct current and voltage for connection of battery packs and supercapacitor units.

The battery pack 11 and the supercapacitor unit with power electronics 12 are connected mechanically comprising a single design. Each battery pack 1 is comprised of the required number of lithium cells connected in series. Contacts of each cell are equipped with equalizing devices intended for monitoring and restriction of cell charge.

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The last battery packs in the raw are connected to switching unit and can be switched to input of the battery pack voltage converter 5. The equalizing devices are connected via data channel with the unit of battery charge monitoring and control 8 equipped with data communication with the voltage converter of battery pack 5. The supercapacitor unit 2 is connected to the switching unit 3 and can be switched to the voltage converter 6. The outputs of the voltage converters 5 and 6 are connected to the input of the bidirectional invertor 7. The output of the bidirectional invertor 7 is connected to the switching unit 4 and can be switched to three-phase electric network at the point of connection to local power stations 14 powered by transmission line 13, as well as to the local three-phase load 15, comprised, for instance, of electric equipment of petrol filling station. The HESS control panel 4 is installed on the switching unit 3 with data communication with the switching unit 3, the voltage converter of battery pack 5, the voltage converter of supercapacitor unit 6 and the bidirectional invertor 7. The voltage converters 5 and 6, and the bidirectional invertor 7 via the switching unit 3 can be switched to the charge stations of electric vehicles 16.

The HESS control panel 4 monitors and controls operation of HESS. The control panel receives the data on variables of electric network, variables of three-phase loads and variables of charge stations of electric vehicles from the switching unit. On the basis of data on HESS operation mode, the HESS control panel determines and transfers instructions by commutation line to the bidirectional invertor, to the voltage converter of battery pack, to the voltage converter of supercapacitor unit, as well as closing/opening commands of contactors of the switching unit. The HESS control unit distributes energy flows between the battery pack and the supercapacitor unit.

The supercapacitor unit compensates rapid variations of load. Due to the fact that supercapacitors allow currents exceeding manifold rated current, in the case of sharp drop of growth of load they can provide optimum route of charge and discharge, thus increasing the resource of lithium batteries and decreasing operation expenses of HESS.

The unit of battery charge monitoring and control receives information on charge of each battery cell and can control equalizing devices for switching of battery cell to load resistances of equalizing device in order to decrease the charge of battery cell. If maximum and minimum allowable charge in at least one battery cell is exceeded, the unit of battery charge monitoring and control can send inhibiting signal to the voltage convertor of battery unit to terminate operation.

The voltage convertor of battery pack receives control signals from the control panel and forms control sequence of pulses for convertor semiconductor switches as well as sends to the control panel the information about battery charge, voltage, current, temperature of batteries and semiconductor switches.

The voltage convertor of supercapacitor unit receives control signals from the control panel and forms control sequence of pulses for convertor semiconductor switches as well as sends to the control panel the information about battery charge, voltage, current, temperature of batteries and semiconductor switches.

The bidirectional invertor receives control signals from the control panel and forms control sequence of pulses for convertor semiconductor switches as well as sends to the control panel the information about battery charge, voltage, current, temperature of batteries and semiconductor switches.

The switching unit switches the units of HESS to the network or load and to charge stations according to command from the control panel.

The major portion of heat loss is generated in semiconductor switches of the bidirectional invertor, the voltage converters of batteries and supercapacitors, therefore, fluid cooling system is provided for their efficient cooling. It would be reasonable to install the semiconductor switches on cooling plates connected to the fluid cooling circuit. The fluid cooling circuit makes it possible to efficiently release heat and, hence, to increase output capacity of HESS and to provide optimum operation conditions of semiconductor switches. In addition, upon such cooling method batteries and supercapacitors are not overheated by heat flow from the bidirectional invertor, the voltage convertors of battery cells and supercapacitor unit.

The fans of compartment of battery cells are used for forced air circulation to remove heat from the compartment of battery cells released upon HESS operation in battery cells, connecting buses and wires, as well as equalizing devices, thus maintaining allowable temperature of batteries and long-term operation lifetime.

The fans of compartment of supercapacitors and power electronics are used for forced air circulation to remove heat from the compartment of supercapacitors and power electronics released upon HESS operation in supercapacitors, components of control panel, switching unit, connecting buses and wires as well as in other devices inside the compartment of supercapacitors and power electronics not included into the fluid cooling circuit.

HESS can operate in three modes:

1) HESS is charged from network via bidirectional invertor;

2) one or more vehicles are charged by transfer of accumulated energy in HESS by means of voltage convertors and energy transfer from network to charge stations by means of bidirectional invertor;

3) uninterrupted power supply to consumers at petrol filling station when the energy accumulated in HESS is transferred to three-phase load by means of bidirectional invertor.

In addition, the HESS design improves usability, maintainability, operation lifetime of batteries and operation safety.

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IV. DISCUSSION

The following advantages of HESS as fast charge of electric vehicles at petrol filling stations can be highlighted:

a) for end consumer (vehicle driver):

- improved power supply due to higher amount of available independent charge stations;

- convenient operation of vehicles due to possible additional services provided at petrol filling stations (shops, car wash, coffeehouses, etc.);

- elimination of territorial limitations for operation of electric vehicles due to better distribution of charge stations;

- backgrounds of cost reduction for charging due to optimization of HESS algorithms enabling maximum efficiency of power supply consumed and accumulated by HESS during the nights at bonus tariffs as well as due to possible competition among different petrol filling stations;

- backgrounds of time reduction for charging due to motivation of petrol filling stations in development and implementation of fast charging aiming at increase in amount of service customers;

b) for national power complex:

- leveling of daily load for power generating facilities;

- extension of power supply market;

- creation of distributed energy storage for the case of emergency situations;

c) for petrol filling stations:

- possibility to cancel the existing methods of redundant power supply of petrol filling stations (generators, etc.);

- minimum investments to improvement of existing petrol station infrastructure;

- diversification of petrol station business due to customer retention (upon conversion from conventional vehicles to electric vehicles) and attraction of new customers;

- potentially high profitability of investments due to minimization of expenses for HESS charging during the nights at bonus tariff;

- potential tax preferences as well as possible release of taxation burden due to minimization of possibility to render poor quality services based on accounting accuracy of energy consumed for charging electric vehicle as well as its consistent quality due to application of HESS.

V. CONCLUSION

Electrification of transport becomes more and more popular in the world due to high environmental safety as well as decrease in expenses of technical solutions for energy accumulation and conversion on board of a vehicle. In order to provide more intensive implementation of electric vehicles, some issue should be resolved relating to development of available infrastructure required for their operation, in particular with regard to arrangement of extensive network of charging stations. It is obvious that most activities on adaptation of existing or creating of new infrastructure facilities are related with funding for capital construction which has detrimental effect on their investment attraction.

As an alternative variant of infrastructural energy supplying facility with relatively high profitability, the method was considered based on integration of fast charge stations into existing low capacity energy system of petrol filling stations using hybrid energy storage system based on lithium-ion batteries and supercapacitors. This would enable fast charge of electric vehicles on the premises of existing petrol filling stations without major modifications of electric networks, herewith, it would be possible to decrease costs of charging due to electric energy stored on HESS during the nights at bonus tariff as well as to provide reserve supply for emergency cases.

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