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Possibilities of Using Innovative Drive Systems for Various Types of Electric Vehicles for Seaports, Container and Logistics Terminals

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ABSTRACT: The article presents the issues regarding the possibility of using innovative drive systems designed by ZAiUP AREX Sp. z o.o. for various types of electric vehicles for seaports, container and logistics terminals. ZAiUP AREX Sp. z o.o. specializes in the design and production of technologies and innovative solutions dedicated to both the civil and military markets. Over 34 years of experience have built a solid and reliable brand. The enduring activity and a number of various projects have allowed us to gain invaluable experience and deepen our unique skills in the projects dedicated to electromobility. This publication presents proprietary technological solutions developed by ZAiUP AREX Sp. z o. o. – an electric drive system that can be used in passenger, delivery and purpose-built vehicles. Thanks to the proposed solutions, the seaports, container and logistics terminals paying attention to cargo operations, security and cybersecurity, as well as energy and innovation, can be improved to become more competitive.

1 INTRODUCTION

The development of the technology of drive systems used in vehicles is currently conditioned by legal regulations, which primarily enforce the reduction of exhaust emissions. These expectations are met by electric vehicles, which are characterized by a complete lack of exhaust emissions at the place of operation. They also do not generate a high level of noise and maintain high efficiency of the drive system at low operating costs. The electric motors used in vehicle drives are also characterized by high dynamics and smaller dimensions in relation to their combustion counterparts. They do not require maintenance or replacement of operating fluids and filters. [3]

Currently, a rapid development of the electric vehicle market becomes apparent. Due to this, the operators of seaports, container and logistics terminals, moving with the times and striving to optimize the working process and reduce expenses, should perceive this development process as a business opportunity that they should take hold of.

Seaports, container and logistics terminals are particularly suitable for automation of equipment and cargo handling procedures thanks to their highly standardised processes, and high throughput and traffic density. Equipment electrification and automation technologies can improve the operational performance, productivity, safety, environmental performance and profitability of terminals. [5]

As part of the research and development project titled the "Development of an innovative propulsion system for mobile platforms" co-financed by the European Union from the European Regional Development Fund under the Intelligent Development Programme (Co-financing Agreement No. POIR.O1.01.01-00-0075/17), Zakład Automatyki i

Urządzeń Pomiarowych AREX Sp. z o.o., WB Group, has developed a promising technology in the field of electric drives and energy storage that uses the latest solutions available on the electromobility market. The company has developed an innovative, fully functional electric platform that enables the construction of electric vehicles, as well as further expansion of transport vehicles for transporting goods and people, as well as special vehicles. Our technology will enable the introduction of effective changes on the market of current tradable solutions in the electromobility industry. [2]

The innovative products offered by the AREX company in the field of electromobility include the following:
- direct drive resulting from the use of torque motors installed in the wheel;
- modular, scalable energy storage;
- integrated drive.

In addition, the company has developed a propulsion platform with an embedded central system that implements predictive control of driving dynamics with energy management.

The product offer of the AREX company is dedicated mainly to integrators – the companies from the automotive industry dealing with electrification of transport platforms. Due to the lack of comprehensive solutions on the market, these companies create power systems and drives used in the construction of electric platforms on the basis of available components usually offered by various suppliers, which causes difficulties in their integration. Therefore, the cooperation with the AREX company offering the ready-made electrical solutions, is a great opportunity to avoid integration problems, which in turn will attract the interest of operators of seaports, container and logistics terminals planning to automate the loading and unloading process along with the optimization of cargo space following the example of other advanced operators in this industry.

This article introduces the basic parameters and advantages of the main components of electric vehicles, such as:
- energy storage system with an advanced POWER management system supervising its operation and ensuring energy supply;
- inverters;
- engines;
- and devices supporting the drive control system.

During the development of the drive system components, the so-called "classical approach" with a central motor was first tested, but later the AREX company also focused on the approach envisaging motors placed in wheels. The main advantages of the latter are:
- reduction of losses due to direct drive transmission;
- retaining more cargo space.

A direct in-wheel motor mounting increases vehicle efficiency and payload by eliminating torque loss generating components such as gearboxes, mechanical transmissions, differentials, drive shafts and gear shafts. The elimination of these elements has a positive effect on reducing the weight of the vehicle, contributing to the reduction of cost spent on vehicle production and environmental protection.

In addition, it increases the usable area of the vehicle, which is an additional attractive asset for maritime operators, and container and logistics terminals.

A relative disadvantage turned out to be a large unsprung mass – which prompts the AREX company to consider applying the solution of this type in e.g. platforms transporting containers at unloading sites / ports, etc., where speeds are relatively low, the quality of the traffic-bearing surface is relatively good, and a large torque is required due to the movement of significant loads, and these are the features of the DWH-200 electric motors developed by our company. An additional advantage of such electrified platforms may be the possibility of their autonomous control, which will translate into increased safety of the personnel handling the loading and unloading operations due to reduction of the risk of 'human error' and the impacts of accidents, as well as will increase the working efficiency in the port. [7]

2 TRANSPORT VEHICLE ELECTRIFICATION SYSTEM

In a conventional transport vehicle with an internal combustion engine, the source of mechanical energy is fuel (gasoline, diesel oil, rarely gas), which is subjected to explosive combustion, mainly with the participation of oxygen from the air. An effective alternative to internal combustion engines is an electric drive characterized by high efficiency of the drive system, smaller dimensions and high dynamics against the backdrop of a complete lack of exhaust emissions and no noise generation. [6]

Against this background, the electrification of any motor vehicle can be accomplished by replacing the current internal combustion engine with an electric motor or installing an additional complete electric drive system. At the same time, the additional electric drive system can be installed, for example, in the form of the motors mounted in the wheels of the vehicle, in line with the existing drive shaft or in the driving axle of the vehicle. The AREX company proposes the use of an electrification system for transport vehicles, in which the electric motor transfers the torque to the axle of the vehicle through the drive shaft. The proposed technological solution enables separate use of the combustion drive driving the front wheels of the vehicle, the electric drive driving the rear wheels of the vehicle, and both drives acting simultaneously in generating mode. [3]

The latter solution makes it possible to charge the energy storages while driving with the use of the internal combustion engine, or to assist the vehicle's braking and charge the energy storage during braking, without losing part of the kinetic energy from the internal combustion engine.

In addition, an important feature of the proposed solution is the ability to replace the energy storages themselves, without having to wait long for them to be charged during working hours. The discharged energy storage can be recharged at night, using the anti-smog tariff, via a stationary or on-board vehicular charger.

Furthermore, introduction of autonomous control to electric vehicles ensures possibility of their operation around the clock 24/7 and even under extreme weather conditions. Autonomous electric vehicles will be able to operate with significantly lower exhaust emissions and noise levels than conventional ones, and such 'non-conventional' vehicle can be used by a seaport or logistics operator company to transport goods between warehouses and container terminals or during stevedoring operations.

Such approach shall add flexibility both to completely new (greenfield) and already operational (brownfield) terminals, the main difference being that the latter require automation to be adapted to the pre-existing conditions and operations, while the greenfield sites enable broader field of actions. [5]

2.1 *A "classic approach" with the DCE-200 central motor and the STS-202 power inverter*

The main driving element of the "classic" electric system developed by the AREX company is a synchronous motor with permanent magnets (neodymium), marked as DCE-200, coupled with a drive shaft (Fig. 1). It is an "inrunner" motor with an inner rotor and a stator bound to the outer casing, intended to be fitted as a central drive of a vehicle with or without a transmission mechanism.

This engine can be used in both heavy and automotive industry, to power passenger cars, delivery vans, utility and special-purpose vehicles. The view of the DCE-200 motor is shown in Figure 1.

The main characteristics of the DCE-200 motor are the following:
- high operating dynamics;
- nominal operating voltage 500 VAC;
- nominal effective current 150 A;
- liquid cooling system (water + max. 50% glycol);
- wide operating temperature range from -40 to +65°C;
- four built-in temperature sensors for precise control of operating conditions and liquid cooling system;
- rotational speed up to 2800 rpm;
- torque up to 2400 Nm;
- built-in rotational speed sensor;
- efficiency level of 96%;
- operation in drive systems with different types of gears;
- operation in a direct drive system (energy efficiency increase up to 10%);
- cooperation with the STS-202 controller;
- possible operation in generating mode.

Figure 1. DCE-200 permanent-magnet synchronous motor. Source: Arex

The 150 kW power inverter, marked as STS-202, has been developed to control the operation of the DCE-200 motor (Fig. 2). The STS-202 power inverter is designed to power and control the operation of AC electric machines used in the electric vehicles, electric working mechanisms, industrial equipment for operation in difficult environmental conditions, etc.

Currently, the STS-202 power inverter is produced in three versions: STS-202-I – in IGBT technology, STS-202-S – in SiC technology, and STS-202-M – in the version for the mining industry.

The basic properties of the STS-202 power inverter are the following:
- power supply voltage 0 ÷ 850 VDC;
- auxiliary power supply voltage 7 ÷ 35 VDC;
- maximum output power 300 kW;
- peak effective current 400 A;
- compact, rigid housing made of anodized aluminium, electrically insulated, protection degree IP67;
- wide operating temperature range from -40 to +105°C;
- liquid cooling (water + max. 50% glycol);
- modern DSP and programmable FPGA;
- built-in protection systems against overcurrent, overvoltage, undervoltage, temperature;
- configurable inputs/outputs (5+2 signals (freely configurable DIO or AIO 0...32 V, two safety inputs – transistors switching off));
- temperature monitoring system of power inverter and motor;
- discharge DC link system;
- Interlock protection;
- memory and events preview;
- communication protocols: 2xCAN, RS-422 (service);
- speed or torque control;
- advanced control algorithm (FOC) for permanent-magnet synchronous motors (PMSM);
- efficiency level of 98%.

Thanks to this, a wide diagnostics of parameters and performed functions is possible using the event recording and viewing system.

Figure 2. STS-202 power inverter. Source: Arex

The STS-202 power inverter can cooperate with the synchronous motors in which the position of the rotor is read with the help of the resolver or Hall sensors.

In order to conduct traction tests of the developed and constructed drive system, the DCE-200 motor was integrated with the STS-202 power inverter in the rear axle drive configuration of the Peugeot Boxer vehicle. The system was powered by the energy storage with a capacity of about 60 kWh and an operating voltage of about 615 V obtained from the assembly of 192 LiFePO4 cells with a capacity of 100 Ah each. The vehicle prepared in this way was subjected to traction tests and tests on a vehicle test facility, showing very promising traction characteristics.

The tests on a vehicle test facility had shown the generated power over 150 kW and the torque reaching up to 2265 Nm.

The results of on-the-road tests are presented in Table 1.

Table 1. Results of on-the-road tests of the drive system consisting of the DCE-200 motor and the STS-202 power inverter.

Maximum speed achieved	over 100 km/h
Distance covered	105 km
Energy consumption	50 kWh
Average energy consumption	476 Wh/km
Estimated range (64kWh storage)	ca. 130 km

Source: Arex

Real-time speed and power curves received during on-the-road tests are presented in Figure 3. Positive power values represent vehicle acceleration processes, while negative ones are the processes related to (regenerative) braking, where energy is accumulated in the vehicle's battery storage.

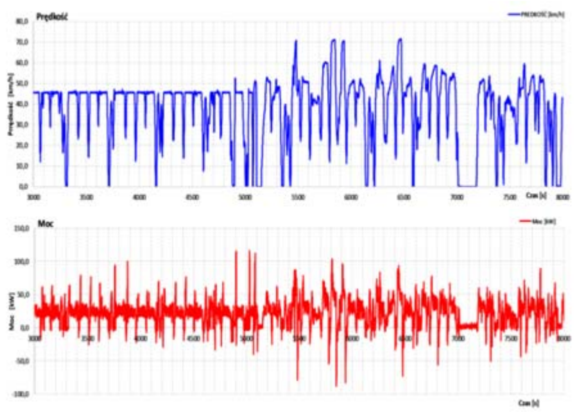

Figure 3. Speed and power curves of the drive system consisting of the DCE-200 motor and the STS-202 power inverter. Source: Arex

2.2 *A "perspective approach" with the DWH-200 in-wheel motor and the STS-203 power inverter*

After successful traction tests of the above-mentioned drive system, it was decided to focus on the next stage of research and development – the development and implementation of a synchronous motor with permanent magnets (neodymium), designated as DWH-200.

It is an "outrunner" motor with an external, rotating body, intended for installation in the wheel hub of the vehicle as a direct drive. Also, an appropriate STS-203 power inverter was designed and manufactured to be used together with this motor. Both devices are shown in Figures 4 and 5 below.

Figure 4. DWH-200 permanent-magnet synchronous motor. Source: Arex

Figure 5. STS-203 power inverter. Source: Arex

The PMSM DWH-200 drive motor is designed for mounting in at least 17-inch rim wheel as a direct drive and is intended for installation in the drive systems of industrial machines operated in harsh environmental conditions, utility and special-purpose vehicles, motor vehicles, hydraulic devices, working mechanisms, and other specialized technical equipment and machines. The design variants if the DWH-200 motor envisage different mounting options depending on the operational needs. The housing material is aluminium or stainless steel, protection level IP65.

The main characteristics of the DWH-200 motor are the following:
– high operating dynamics;
– nominal effective current 150 A;
– max. torque 1000 Nm;
– nominal rotational speed 1200 rpm;
– liquid cooling system (water + max. 50% glycol);
– wide operating temperature range from -40 to +50°C;
– built-in temperature sensors;
– built-in rotational speed sensor;
– operation in a wide range of rotational speed;
– operation in drive systems with different types of gears;

– operation in a direct drive system (energy efficiency increase up to 10%);
– possible operation in generating mode;
– efficiency level of 96%;
– connection box (3x high power terminals – max. 35 mm^2 Cu);
– signal connector (4x Thermistor PTC, Resolver, 3xHall).

The second basic element of the drive system with the DWH-200 motor is the 40 kW power inverter, marked as STS-203.

The STS-203 power inverter is designed to power and control the operation of AC electric machines used in the electric vehicles, electric working mechanisms, and industrial equipment intended for operation in difficult environmental conditions.

The basic properties of the STS-203 power inverter are the following:
– power supply voltage 0 ÷ 850 VDC;
– auxiliary power supply voltage 7 ÷ 35 VDC;
– max. output power 80 kW;
– peak effective current 150 A;
– compact, rigid housing, electrically insulated, protection degree IP67;
– operating temperature range from -20 to +50°C;
– external cooling;
– modern DSP and programmable FPGA;
– built-in protection systems against overcurrent, overvoltage, undervoltage, temperature;
– configurable inputs/outputs (5+2 signals (freely configurable DIO or AIO 0...32 V, two safety inputs);
– transistors technology: SiC;
– temperature monitoring system of power inverter and motor;
– discharge DC link system;
– Interlock protection;
– memory and events preview;
– communication protocols: 2xCAN, RS-422 (service);
– speed or torque control;
– advanced control algorithm (FOC) for permanent-magnet synchronous motors (PMSM);
– efficiency level of 98%.

First, a man-driven prototype platform equipped with in-wheel motors of this type (DWH-200) have been built (Fig. 6a), followed by their installation and performance of practical tests as a rear drive of the vehicle (3.5T) of the Peugeot-Boxer type in a 4x2 front combustion drive configuration (factory) and a 4x2 rear electric drive (Fig. 6b).

Figure 6a. A man-driven prototype platform equipped with the in-wheel DWH-200 motor. Source: Arex

Figure 6b. DWH-200 motor mounted as a rear-drive configuration of the Peugeot Boxer. Source: Arex

For safe operation of the motor, the liquid cooling with a maximum flow of 20 l/min of coolant at a temperature below 65°C is necessary. At the same time, the STS-203 power inverter is passively cooled, which is completely sufficient for the power inverter design with power modules in SiC (silicon carbide) technology. For the cheaper version based on silicon technology with IGBT modules, it is also possible to implement active cooling after adding a special cooling plate. [3]

2.3 *Energy storage*

As part of the works related to the aforementioned project, two types of energy storages have been developed and manufactured.

The first type was the 10 kWh battery module with adjustable output voltage, marked as BMU-200, based on Li-ion NMC 3.6 V cells in the 18650 standard with a capacity of 3 Ah each.

In order to build the desired current and voltage capacity, a parallel connection into a set of battery modules is used. The connection safety is ensured by a 2-directional DC/DC converter with a peak power of 30 kW built into each battery module. The programmable DC/DC converter allows you to maintain a constant operating voltage on the DC Link of the powered device (e.g. power inverters controlling motors), regardless of the voltage of the battery cell module.

The use of an intermediate converter gives full security when connecting battery modules in a configuration with a scalable capacity. In addition, thanks to the use of a converter, it is possible to combine energy storage devices made in different technologies (chemistry) of cells, with different nominal operating voltages and with different usage histories.

Thus, the basic properties and advantages of the BMU-200 battery module are the following:
– built-in DC/DC converter enabling a wide range of output voltage;
– possibility of flexible parallel connection with Li-Ion battery modules with different output voltage, SOC, SOH, DOD;
– the module is prepared for mounting in a rack equipped with quick connectors for easy assembly and disassembly;
– modular design enabling the use of 1 to 8 modules;

– compact, rigid housing ensuring safety in terms of mechanical and thermal working conditions of the module, protection degree IP65;
– wide operating temperature range from -40 to +60°C;
– thermal liquid conditioning;
– multi-stage, built-in protection systems: overcurrent, overvoltage, undervoltage, temperature;
– safety inputs (stop of the converter operation, disconnection of contactors);
– pre-charging system, HV fuse, safety contactors on both poles of the module;
– protection against reverse polarity of the auxiliary power supply voltage;
– measurement of the voltage and current of the module, measurement of the voltage on the cell side;
– advanced cell operation control system – measurement of temperature, voltage, current, estimation of SOC, SOH, DOD, limit values of load currents;
– passive balancing of cells;
– memory and events preview;
– communication protocols: 1xCAN for the master device, 1xCAN for parallel connection of modules, 1xRS-422 for service purposes;
– efficiency level up to 98%.

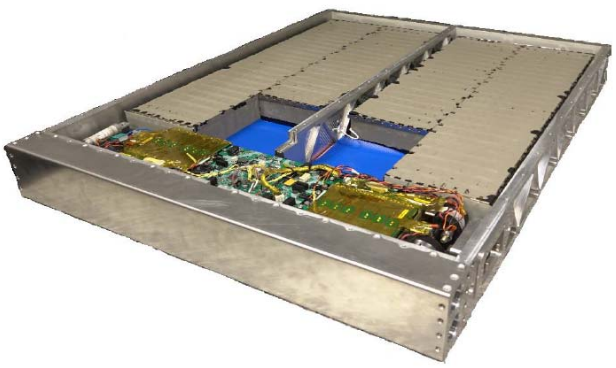

Figure 7. The interior of the BMU-200 battery module with a maximum capacity of 15 kWh, operating voltage of 600 V controlled by a bi-directional DC/DC converter with a load capacity of up to 30 kW. Source: Arex

The above-mentioned BMU-200 battery module has a higher energy density, but is also a more expensive technology.

Therefore, the AREX company has also developed a second, less expensive type of energy storage based on proven prismatic cell technology, namely the 10 kWh battery module, marked as BMU-202.

The BMU-202 battery module has the following features:
– modular design;
– the module is prepared for mounting in a rack enabling easy assembly and disassembly;
– compact housing ensuring safety in terms of mechanical and thermal working conditions of the module, protection degree IP44;
– wide operating temperature range from -40 to +60°C;
– integrated BMS enabling passive balancing of cells;
– advanced cell operation control system – measurement of temperature, voltage, estimation of SOC, SOH, DOD, limit values of load currents;
– HV fuse integrated with the service switch;
– communication protocols: 1xCAN for the master device.

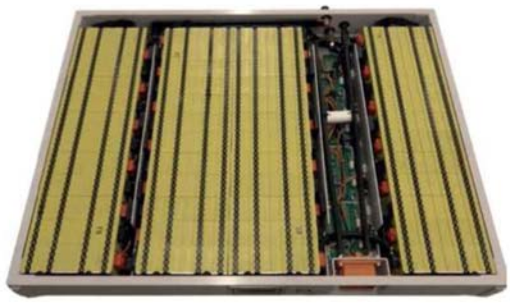

Figure 8. The interior of the BMU-202 battery module with a maximum capacity of 10 kWh, made of LiFePO4 prismatic cells with a capacity of 60 Ah each. Source: Arex

Additionally, as part of the research and development project, an on-board DC/DC (HV/LV) converter 1.5 kW (12V) / 3.0 kW (24V) was developed and manufactured, marked as PSU-203. The PSU-203 DC/DC converter is designed for powering the low voltage (LV) on-board devices from high voltage (HV) battery power source, charging lead batteries in CC/CV modes, and buffer operation with 12/24V lead battery with charging function in accordance with programmed charging characteristic and battery parameters monitoring (voltage, current, temperature).

The basic features and advantages of the PSU-203 DC/DC converter are the following:

– various working modes: power supply, buffered power supply, battery charger;
– CC/CV charging modes;
– scalable output power and possibility of parallel connection;
– high stability of output current and voltage;
– liquid cooling (water + max. 50% glycol);
– possibility of cooperation with the superior system;
– modern DSP;
– dedicated to lead batteries;
– function of compensation of voltage drop on DC cables;
– temperature compensation of the charging voltage;
– programmable battery charging characteristics;
– built-in protection systems: short-circuit, overload, voltage, reverse polarity, temperature;
– communication protocols: 2xCAN, RS-422 (service);
– register of events and alarms;
– wide operating temperature range from -40 to +70°C;
– efficiency level of 94%;
– housing material: painted, anodized aluminium, protection degree IP67.

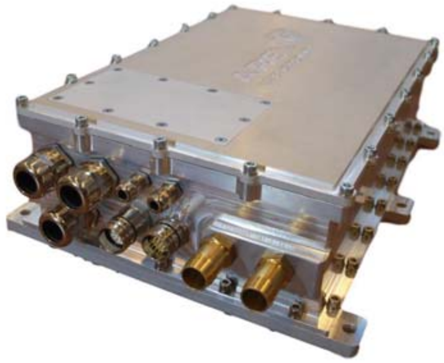

Figure 9. PSU-203 on-board DC/DC converter. Source: Arex

Thanks to the proven technology, the PSU-203 on-board DC/DC converter ensures the safety of DC/DC (HV/LV) 1.5 kW (12V) / 3.0 kW (24V) power supply.

3 CONCLUSIONS

As a result of traction tests of electric drive systems developed as part of the research and development project, we come to the following conclusions:

1. The car manufacturers and integrators from the automotive industry are increasingly paying attention to the use of electric drive system technology in their products, thanks to such operational advantages as the lack of exhaust emissions and noise at the place of their operation, high operating dynamics and high torque generated by the engine in full speed range, low operating costs, simple design and a small number of mechanical components.
2. The positive synergistic effects of using an electric drive system can be even better when electric machines mounted in the wheels of the vehicle are used for the drive. A direct in-wheel motor mounting increases vehicle efficiency and payload by eliminating torque loss generating components such as gearboxes, mechanical transmissions, differentials, drive shafts and gear shafts. The elimination of these elements has a positive effect on reducing the weight of the vehicle, contributing to the reduction of cost spent on vehicle production and environmental protection. In addition, it increases the usable area of the vehicle, which is an additional attractive asset for maritime operators, and container and logistics terminals.
3. A relative disadvantage of using direct electric drives – the in-wheel motors – turns out to be a large unsprung mass, which, however, will not cause significant awkwardness in case of using such solutions in e.g. platforms transporting containers at unloading sites / ports, etc., where speeds are relatively low, the quality of the traffic-bearing surface is relatively good, and a large torque is required due to the movement of significant load, and these are the features of the DWH-200 electric motors developed by the AREX company.
4. The final effect of the works related to the project is the creation of a comprehensive solution enabling the so-called integrators to perform easy construction of electric vehicles, especially transport ones, but also specialized vehicles for service stations, repair teams or groups working at unloading sites / ports to perform various specialized loading and unloading operations and increase the efficiency of work in the port, including such activities achieved through the prospective development of electrified platforms to the level of remotely controlled vehicles and even autonomous systems.

To summarize, years of experience of the AREX company dealing with a number of various innovative completed projects have led the company to become an expert in the field of projects implementation, which gives us the basis for setting further ambitious goals in the electromobility, envisaging the following steps:

1. Establishment of non-binding collaboration with the Baltic Container Terminal Gdynia for precise investigation of possibility to implement the electromobility solutions for cargo handling operations.
2. Teaming-up with higher educational institutions in the sphere of development and further implementation of systems for autonomous control of the presented electrical platforms.

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