Increased controllability of the distributed traction system in emergency mode

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***Abstract*—The puprose of the work is to improve approaches to the controllability of power consumption in distributed power systems of electric rolling stock using modern technologies and equipment. Unequal energy consumption on the shoulders of the power supply causes additional losses in the system and makes the voltage mode worse on the current collectors of electric locomotives. To increase the controllability of operation modes, is proposed to use feeder volt-additional converters with arcless commutation of short-circuit currents. Using such converters allow to stabilize the voltage on the current collectors of electric locomotives and reduce the switching-off time. Variant calculations using the proposed circuit engineering of traction substations on the simulation model prove that the power losses from the equalizing currents are significantly reduced**

Keywords— distributed traction power system, traction substation, proximity switch, volt-additional converter

I. Introduction

In case of 3.3 kV voltage level in the DC traction network for the implementation of high-speed motion, the use of distributed power supply circuit engineering is an uncontested to providing the required energy indicators. To date, several approaches to the construction of distributed power systems for electric traction of direct current [1] have been formed:

- with power supply of AC points (10, 35 kV) evenly distributed over the feeder zone of boost points (BP);

- with power supply to BP with a direct current line (6, 12, 24 kV);

- with power supply to the BP from alternative sources of electricity;

- with the use of single-unit traction substations inside the feeder zone.

Despite the applied distributed power supply (DPS) scheme, the following factors must be considered:

- reducing the power zone changes the characteristic of energy processes in the traction network in both normal and emergency modes. In addition to developing new calculation methods [2], it is necessary not only to change the settings of the relay protection [3], but also to increase the reliability of switching emergency modes;

- the operation of the DPS takes place in a "forced mode", that is forced (but not controlled) distribution of available power in the system of power supply system depending on the consumption levels in adjacent feeder zones;

- due to the unequal loading of the feeders, accordingly, different voltages on the tires of the traction substations, the voltage losses in the feeder zones increase as a result of

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additional equalizing currents during the forced redistribution of energy flows;

- the use of DPS requires the development of new circuit engineering of both traction substations and boost points, the main differences of which are maximum unification and less aggregate capacity.

The operation of the traction power supply system is characterized by the complex interaction of technological processes of transmission, transformation and consumption of electricity in the transportation. In order to increase the efficiency of energy exchange processes, it is necessary to take into account the specific conditions of electrified area operation: the connection places of power sources and their type, track profile, trains schedule, used types of electric rolling stock and equipment.

The processes of power consumption in the traction network occur under conditions of different insurges: changes in the operating modes of electric rolling stock depending on the train schedule, track profile and existing restrictions, short-term disconnections of current collectors and various transient processes, which can lead to emergency modes. It should be noted that in the normal mode of operation, the existing power supply systems for electric rolling stock are limited to control energy flows and determined by the power supply circuits of the traction network, used equipment and the circuity engineering of traction substations, which does not meet modern requirements. These factors lead to develop new approaches to improve the control of electricity flows in the developed distributed traction power systems in both emergency and normal modes of operation.

II. Material and Method

Protection against short-circuit currents (SCC) for DC traction networks is one of the most relevant and at the same time the most difficult problems, as long as the determination of short-circuit currents is complicated by small difference between the maximum operating load currents and the minimum short-circuit currents. Today, high-speed circuit breakers (BW) are the main switching devices in DC traction substations, because they must control disconnection during short circuits and overloads in order to avoid negative consequences of the emergency currents effects on the equipment of substations and the contact network. At the same time, they can fulfill the function of protecting the feeders of the contact network and additional functions related to the operation of automation elements and, in some cases, control the accuracy of the actions taken when performing certain operations related to switching devices in the power supply system.

Currently, on railways that are electrified with direct current, several types of high-speed circuit breaker are used: AB-2/3, AB-2/4, VAB-2, VAB-28, VAB-43, VAB-49, VAB-70, VAB - 206, GE Rapid 4207, which are installed on feeders of traction substations, sectioning posts and parallel connection points. In DC circuits the high-speed circuit breaker shall provide reliable arc quenching during an emergency disconnection when a direct short-circuit current reaches 20-30 kA, which occurs in the case of a short circuit near the substation, while there is a need to quench the arc at currents less than 100 A during an operational disconnection.

In the literature on the theory of protection of DC traction networks, a simplified equivalent circuit shown in Fig. 1. In this diagram, Lтм and Rтм are the inductive and active resistance of the traction network, Lp and Rp are the inductive and active resistance of the reactor.

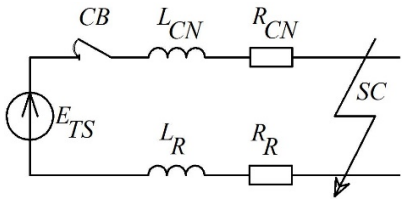

Fig. 1. The simplest short circuit equivalent in the traction network

The current in this scheme is described by the following equation:

$$i(t) = I_0 + \Delta I\left(1 - e^{-\frac{t}{T_c}}\right) \quad (1)$$

Tc is the circuit time constant equal to the ratio of inductance to electrical resistance.

The calculated current and voltage curves according to (1) are shown in Fig. 2.

It should be noted that the flow of transients in case of a short circuit is affected by the smoothing filters and discharge devices used at the traction substations. The use of filters increases the rate of current change, and the discharge devices improve the conditions of quenching of the electric arc in the high-speed circuit breaker. The real curves of current and voltage at short circuit, obtained as a result of performed experimental studies at the Department of ISE, differ from the theoretical ones (Fig. 3). Comparing Figures 2 and 3 at the stage of short-circuit occurrence in real conditions, an oscillatory process is observed in the current and voltage curves, the account of which is necessary for the proper functioning of relay protection.

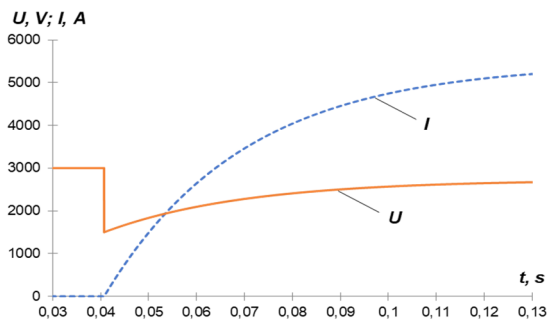

Fig. 2. Idealized curves of current and voltage at short circuit in the traction network

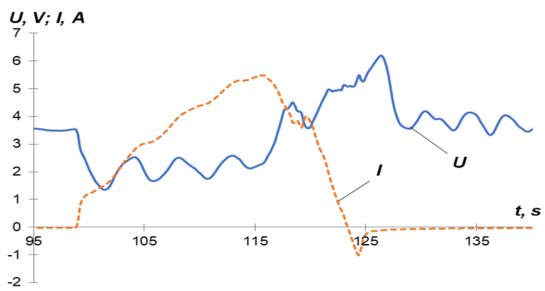

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Fig. 3. Typical process of development and disconnection of short circuit current

One of the main disadvantages of using mechanical-driven high-speed circuit breaker which can interrupt fault currents for several ms is unreasonable slowness, which does not allow reliable protection of the DC network [4]. The intensive development of power semiconductor technology makes it possible to create powerful contactless switches and converters [4-6]. Nowadays the production of GCT - and IGBT-thyristors with a load capacity of up to 6000 A for a voltage of up to 8000 V is possible [7]. Therefore, different types of hybrid switches with arcless current switching are being developed as DC switches. Their variant designs have insignificant energy losses, while maintaining the ability to quickly interrupt the current. Their most promising design, especially for the voltage level in the traction network of 3 kV, is a combination of voltage regulation and load switching functions in one device [6, 8].

Traction substations of electrified railways (TS) are characterized by multifunctionality related to the need for power supply of electric rolling stock and non-traction and district consumers. The DCs in use are powered by 110-220 kV power systems and use powerful transformers and converters. But according to the operating experience the coefficient of power mode and traction substations equipment using does not exceed 15% [9]. Therefore, while implementation of high-speed traffic, it is necessary to meet not only the requirements of normalized voltage and energy intensity of the traction network, but also to form new approaches to the circuit engineering of traction substations in order to increase the efficiency of electricity use. In addition to the above requirements, a modern traction substation must not only be integrated into a single intelligent control system [10] but also have sufficient means to control the power modes in normal, forced, and emergency modes.

As it is known, in the case of a distributed power supply, in order to ensure normal dimensions of movement, it is necessary to locate substations much closer to each other than in the scheme of centralized power. Accordingly, the capacity of each substation will be lower and their number is higher. Ukrainian scientists have developed a traction unit PA-5200 [8, 11] with a capacity of 5.2 MW to use it in distributed power systems.

The development of the prototype of the PA-5200 converter unit is based on the research work on the development of technical requirements for the converter units based on twelve-pulse semi-controlled volt-additional rectifiers for DC traction substations, under the guidance of prof. Goncharova Yu.P. and Panasenko M.V.

According to the studies [12], the indicated aggregate power is sufficient to provide the necessary energy indicators and the stability of the power system during high-speed movement.

To implement the principle of controlled redistribution of available power in the system, it is necessary to fulfill the following conditions [13]: voltage regulation in the contact network, raising equalizing currents in the intersubstation zone of electrified areas to a minimum value, ensuring reliable regenerative braking by automatically reducing the voltage on the tires of adjacent traction substations during the transition of an electric locomotive into recovery mode, limiting the permissible load currents of the wires of the contact network due to their overload distribution between adjacent traction substations.

The solution to these problems in this work is assigned to voltage control devices, made either by adjustable rectifiers or rectifiers, supplemented by voltage-sensitive devices with non-contact automatic regulation of rectified voltage. At the same time, the regulation of the voltage on the traction substation tires does not completely solve the existing problem, due to the increased power losses at the intersubstation zone and the corresponding operating costs [14]. The main disadvantage of regulating the voltage at the traction substation is that when the feeders are unevenly loaded, there is a factor of "over-regulation and under-regulation" and the voltage across the current collectors of the electromotive composition of different power zones will be different. As shown by the variant calculations made at the ICE department, the forced power distribution under such regulation increases to 15% the magnitude of voltage changes at the electric locomotive current collectors and increases to 10% power loss due to the currents leakage. It implies the natural need for feeder-based voltage regulation depending on the level of traction load and the improvement of circuitry of traction substations and boost points, and, accordingly, of the existing circuitry of DPS (Fig. 4). It is necessary to carry out the transition from the existing circuitry of traction substations (Fig. 5) to a traction substation circuit with devices for feeder-based voltage regulation and VDC switching (Fig. 5). A noteworthy detail is that we are only considering the DC system.

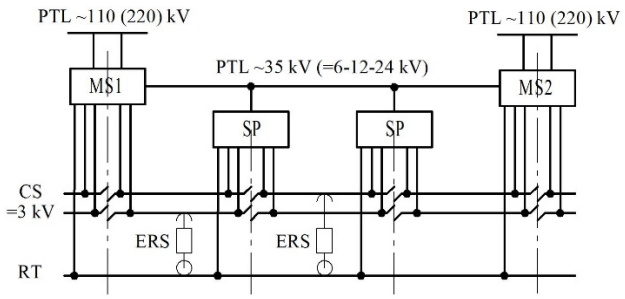

Fig. 4. Block diagram of distributed power system: MS – main substation, SP - supply point, RT – rail track; CS – catenary system; ERS – electric rolling stock

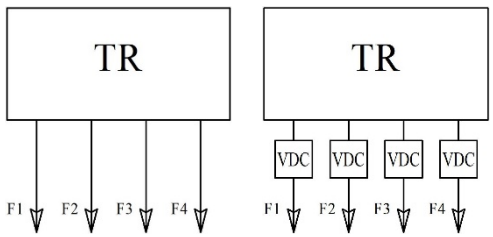

Fig. 5. Simplified scheme of traction substation: TR – traction unit, VDC – volt-additional converter with arcless commutation, F – contact network feeders

By contrast with the proposed structures of the converter-switchgear [6] and the converter unit [8, 11] with a voltage-sensitive converter and a short-term current limiting function, we propose to use an active rectifier proposed in [12] at the traction substation, and the functions of additional voltage regulation and short-circuit current limits put on the device feeder voltage regulation and switching VDC. This device is a separate converter unit with fully controllable

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thyristors with a depth of adjustment of the output voltage of ± 500 V and a working current of up to 3 kA. The use of dual-operating semiconductor devices also allows the implementation in this scheme of limitation of surge current in emergency modes. The installed power of the VDA device is several times less compared to the power of the main rectifier and can vary within 0.5 ÷ 1.5 MW depending on the operating conditions of the electrified area and the accepted normal power supply circuit. Modeling the operation of the proposed structure of the traction substation in the Mathlab Simulink environment using the Power Electronics package was carried out using the iSET Intelligent Transport Power Supply System software package developed at the ISE department [15]. This software is designed to calculate the mode performance of the traction power supply system for DC and AC railways, namely feeder and primary currents, distribution of currents in the contact network, voltage loss, power, electricity consumption, and the main power quality indicators in the traction power system taking into account the technical means of improving the quality of electricity. Performing optimization calculations of the optimal parameters of the traction power supply system and determine the laws control of technical means in order to increase the efficiency of the traction power supply system operation mode. The simulation results are presented in Fig. 7 and 8. Their analysis shows that when using feeder volt-additional units with arcless switching of short-circuit currents, the range of voltage changes at electric locomotive receivers decreases by 21%, with the switch-off speed is almost twice high. Conducted variant calculations on the simulation model prove that the power losses during the forced redistribution of power between the traction substations from the equalization currents are reduced by 70-80%.The solution to these problems in this work is assigned to voltage control devices, made either by adjustable rectifiers or rectifiers, supplemented by voltage-sensitive devices with non-contact automatic.

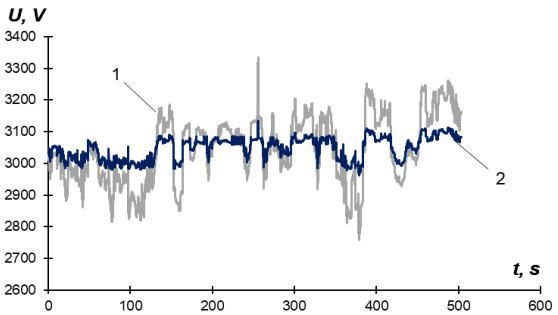

Fig. 6. Voltage mode on the electric locomotive current collector: 1 - when using traditional traction substation circuitry, 2 - when using feeder volt-additional units with arcless switching

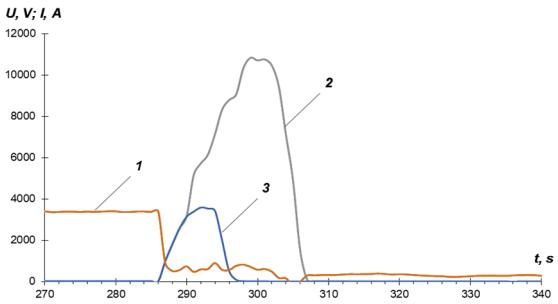

Fig. 7. Modeling the operation of the emergency current limiting mode during short-circuit: 1 - voltage level on the traction substation tires, 2 - current change graph during the operation of the high-speed circuit breaker, 3 - current change diagram during the operation of the feeder volt-additional aggregate with arcless switching

III. Conclusions

The use of distributed traction load is the most advanced means of implementing high-speed trains. At the same time, its application requires the improvement of the traction substation circuitry to improve energy performance and improve their controllability in different operating modes.

The proposed method of feeder control of electricity flows allows to provide the necessary mode of voltage on the current collectors of electric locomotives in the introduction of high-speed movement while increasing the energy performance of the traction power supply system. At the same time due to the use of feeder volt-additional switches with the mode of current exchange in the event of emergency modes, the controllability of the processes of power consumption increases significantly.

As feeder volt-additional units with arcless switching of short-circuit currents, it is proposed to use a transformer unit on fully controlled thyristors with a depth of ± 500 V output voltage and a working current up to 3 kA. The installed capacity of this unit is several times smaller than the power of the main rectifier and can vary within 0.5 ÷ 1.5 MW depending on the operating conditions of the electrified area and the accepted normal power supply scheme..

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