A new approach to thyristor-based converter commutation configuration for AC-wire DC-motor electric locomotive traction and energy regeneration modes

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Abstract. The widespread use of power converters in modern electric locomotives provides multiple opportunities for railway electric transport, one of them being smooth supply voltage regulation. For electric locomotives with smooth voltage regulation the overall efficiency of energy consumption is dependent on power factor of its power converters, both in traction and regenerative braking modes. Power factor of thyristor-based converters universally used on Russian railways remains to be relatively low. The paper presents a technical proposal to modernize the type AC-wire DC-motor electric locomotive power circuit by introducing a semiconducting discharge shunt in parallel with the subcircuit of rectified current, which allows for a revision of the traditional control algorithm of the converter’s thyristor arms. Mathematical modelling of the proposed circuit suggests a 4.6 % increase in converter power factor in traction mode and an 18.5 % increase in regenerative braking mode under nominal load conditions.

1. Introduction

In 1960s, in order to suit its railway system undergoing electrification with 25 kV 50 Hz AC, the USSR began construction of new AC-wire, DC-motor electric locomotives equipped with thyristor-based power converters that allowed for energy rectification and inversion. Reversible power converters (RPCs) onboard modern Russian AC-wire DC-motor locomotives are the most sensitive and expensive elements of the electric drive. RPCs allowed to implement regenerative braking as well as smooth supply voltage (and by extension, speed) regulation. They also serve as a basis for introduction of automatic control systems, facilitating automation of train operation [1, 2].

The existing experience in RPC application has ensured sufficiently high overall efficiency of electric locomotive operation on Russian railways [3]. However, further progress in traction energy consumption reduction is yet to be made. Locomotive energy consumption is largely dependent on power converters’ power factor, which peaks at 0.84 for contemporary locomotives with thyristor-based RPCs in traction mode and is less than 0.65 in regenerative braking mode. Low power factor...
means locomotives create considerable amounts of reactive power that loads the overhead line, limiting its through-put capacity as well as reducing power quality (i.e. distorting the grid waveform).

Such deficiency in power factor arises from a substantial phase shift $\varphi$ between supply voltage and current waveforms. For traction mode, this shift results from long duration of two time intervals ensured by the type control algorithm: the so-called “thyristor firing angle” $\alpha_0$ and “thyristor commutation angle” $\gamma$. Both are non-regulated and hardwired into the algorithm, as they are required for stable rectification.

For regenerative braking mode on the other hand, the considerable $\varphi$ is caused by an even larger interval called “thyristor firing advance angle” $\beta$, also necessary in the control algorithm.

The minimum value of $\alpha_0$ in type RPCs is usually set to 7-11 electrical degrees (º) and is dictated by the necessity to create potential conditions for anodes of firing thyristors, which habitually work in adverse conditions (overhead line voltage distortion, high energy load due to multiple trains within the feeder zone, etc.) [4]. Long duration of the commutation angle $\gamma$ is due to the “by-turn” principle of commutation applied in the control algorithm. Finally, the substantial value of $\beta$ is required to ensure stable work of energy regeneration and eliminate the possibility of a catastrophic failure event known as the “inverter turnover”, which may short-circuit converter thyristor arms.

2. Type AC-wire DC-motor electric locomotive power converter

The type RPC addressed in the paper, based on an 8-arm thyristor bridge and providing 4 voltage regulation zones, has been designed over 50 years ago. First implemented on the VL80R freight locomotive series, it became standard for all domestic AC-wire DC-motor locomotives and electric multiple units. The control algorithm of this RPC applies by-turn commutation, where a complete switch between two groups of thyristors every half-period is executed in two steps: the two more distant thyristor arms (the “larger circuit”) switch first, then the two closer arms (the “smaller circuit”) switch second [5]. As a result, the total duration of this complete thyristor commutation cycle substantially lowers power factor.

Figures 1 and 2 demonstrate main electromagnetic processes of a type RPC operating on its 4th voltage regulation zone in traction mode. The graphs are obtained from a VL80R series mathematical model in MATLAB Simulink environment.

Figure 1. Diagrams of rectified voltage and current on 4th voltage regulation zone in traction mode.
Some technical proposals have been suggested before to increase power factor by improving converter control algorithm within the existing electric drive elemental structure. Papers [6-8] explore electromagnetic processes that accompany thyristor arms commutation and introduce different control algorithms. However, aiming to improve the adopted control algorithm without modernizing the electric drive structure has proved to offer minimal effect. Application of one of the referenced proposals increased locomotive total power factor by only 1.84%.

3. Diode discharge shunt

Papers [10, 11] present comprehensive analytic and experimental research of implementing a simple diode arm in the electric drive that shunts anode and cathode busbars of the converter and provides a discharge circuit for the control algorithm to apply in thyristor commutation.

Figure 3 illustrates a simplified electric drive power circuit with a diode discharge shunt (VD) in parallel with the subcircuit of rectified current. Figures 4 and 5 demonstrate its main electromagnetic processes.

Inclusion of a discharge shunt allows to introduce a designated buffer circuit within the control algorithm that activates during a specific phase to discharge reactive power accumulated inside the rectified current subcircuit. Due to this, reactive power circulates through the buffer circuit and discharges in traction motors (M1, M2) during thyristor arms commutation, thus contributing to
tractive effort. The share of active power in total apparent power supplied by the electrical grid also increases.

The introduction of the diode discharge shunt opens a possibility to rationalize the control algorithm, as now the diode conducts electricity at the beginning of every AC half-period, discharging accumulated energy in traction motors. It allows to abandon the firing angle $\alpha_0$ and execute thyristor arms commutation immediately at the start of every half-period. This leads to a decrease in phase shift $\phi$ between voltage and current waveforms, a rise in the rectified voltage mean value and a smaller rectified current pulsation coefficient. Consequently, power factor in traction mode increases by 2.68 % [10]. The technical proposal has been implemented on the 3ES5K series freight locomotive No. 879 and successfully tested on the East Siberian Railway.

![Figure 4](image1.png)

**Figure 4.** Diagrams of rectified voltage and current with a diode discharge shunt on 4th voltage regulation zone in traction mode.

![Figure 5](image2.png)

**Figure 5.** Diagrams of thyristor arm currents with a diode discharge shunt on 4th voltage regulation zone in traction mode, $\alpha_0$ set to 9º.

However, this solution to low power factor issue is also not absolute. In addition to the marginal
value of power factor increase, the diode discharge shunt only works in traction mode and should be switched off during energy regeneration, meaning lack of any positive change for the latter. The switching between operation modes is executed by a comparatively unreliable mechanical contact (QT) mounted on the locomotive’s main brake switch.

Further research of the proposal only focused on other ways of introducing the diode shunt between anode and cathode busbars of the converter [9, 10].

4. Diode-transistor discharge shunt
The authors of the paper suggest a further revision of both the electric drive elemental structure and the control algorithm. This can be achieved by applying modern semiconductor devices that can be switched on or off by the gate control signal alone. IGBTs with their high performance, well-studied failure mechanisms and overall maturity in power electronics industry application [11] were considered to be the ideal choice by the authors.

Figure 6 presents a simplified electric drive power circuit with a discharge shunt that consists of a diode (VD) and a transistor (VT).

In this circuit, an increase in power factor of the converter in both operation modes is achieved by shunting the rectified current subcircuit with a fully controllable diode-transistor arm, with the diode’s cathode connecting to the converter’s cathode busbar, and the transistor’s collector to its anode busbar.

Transistor control in traction mode is executed by transmitting the enabling signal to its gate at the start of every half-period of a complete AC cycle, which may be written down as ot = 0° for every first half-period and ot = 180° for every second half-period. The conductive state of the shunt then lasts for about 30°, during which the shunt helps to accelerate commutation between thyristor arms (see figure 5), and then ends with the next firing thyristors naturally switching the shunt off. Thus, the enabling signal can be removed at ot = 35° / ot = 215° for the first and the second half-periods respectively [12, 13].

For regenerative braking mode, the shunt is switched on by the enabling signal of its transistor at ot = 155° / ot = 335° and switched off by removing the signal at ot = 205° / ot = 25°. This way, the working period of the shunt is arranged symmetrically to the end points of every half-period.

The described revision of the converter’s control algorithm results in a significant decrease in phase shift φ, which in turn decreases reactive power portion in energy supplied by the grid. The consequent rise in power factor of the new converter reaches 0.89 in traction mode and 0.87 in regenerative braking mode for 4th voltage regulation zone under nominal load conditions.

5. Conclusion
A significant increase in AC-wire DC-motor thyristor-based electric locomotive power factor in traction and regenerative braking modes can be achieved by implementing a discharge shunt that is
connected to the rectified current subcircuit of the main power circuit. The proposed shunt consists of a diode and a transistor in series, with its diode cathode connected to the cathode busbar of the converter, and its transistor collector to the anode busbar.

The introduction of the discharge shunt allows for a complete revision of the existing control algorithm of the converter’s thyristor arms. The shunt serves as a designated buffer circuit within the algorithm that activates during a specific phase to discharge reactive power accumulated inside the rectified current subcircuit.

Mean power factor increase for the new converter amounts to 4.6 % in traction mode and 18.5 % in regenerative braking mode under nominal load conditions.

References
[1] Tikhmenev B N and Kuchumov V A 1988 Alternating Current Electric Locomotives With Thyristor Converters (Moscow: Transport Publishing House) 311 p
[2] Chantieva M E, Dzhabrailov K A, Iluhin A V, Gematudinov R A 2019 Software Optimization Methods for Composite Materials 2019 Systems of Signals Generating and Processing in the Field of on Board Communications doi:10.1109/sosg.2019.8706771
[3] Nekrasov O A, Lisitsyn A L, Muginshtein L A and Rakhmaninov V I 1983 Mainline Electric Locomotives Operating Modes (Moscow: Transport Publishing House) 231 p
[4] Tikhmenev B N, Basov Yu A and Nakhostin V V 1984 Thyristor Potential Operating Conditions of VL80R Electric Locomotive Reversible Power Converter. Electric Braking of Electric Rolling Stock. Collected Papers of VNIIZhT (Moscow: Transport Publishing House) 9–21
[5] Lozanovskiy A L 1984 Energy Parameters of Domestic AC Electric Locomotives. Collected Papers of VELNII vol 25 (Novocherkassk: VELNII Press) pp 58–68
[6] Vlasyevskiy S V and Melnichenko O V 2003 Power factor increase possibilities for AC electric locomotives with thyristor converters Herald of MIIT vol 10 (Moscow) pp 35–40
[7] Vlasyevskiy S V and Melnichenko O V 2004 Application of a diode discharge shunt in an AC electric locomotive multizone rectifier Herald of JSC VELNII vol 2 (Novocherkassk: VELNII Press) pp 127–134
[8] Vlasyevskiy S V, Semchenko V V and Melnichenko O V 2015 Patent No RU2561913 (Moscow: Rospatent)
[9] Melnichenko O V and Vlasyevskiy S V 2004 Energy saving control algorithm for an electric locomotive multizone rectifier with an uncontrolled gate diode arm Energy Saving Technologies and The Environment. Int. Conf. Heads of Reports (Irkutsk) pp 30–31
[10] Vlasyevskiy S V, Babichuk A K and Melnichenko O V 2008 Patent No RU2322749 (Moscow: Rospatent)
[11] Yang S, Bryant A, Mawby P, Xiang D, Ran L and Tavner P 2011 An industry-based survey of reliability in power electronic converters IEEE Transactions on Industry Applications vol 47(3) pp 1441–1451
[12] Melnichenko O V 2013 Mathematical modelling of electric locomotive reversible power converter with type and proposed control methods in emergency operation conditions Modern technologies. System analysis. Modelling vol 4(40) (Irkutsk: Publishers of Irkutsk National Research Technical University) pp 229–233
[13] Boginskiy S A, Melnichenko O V and Linkov A O 2019 Increasing AC-wire DC-motor electric locomotive power factor by reorganizing grid commutation of reversible power converter arms Modern technologies. System analysis. Modelling vol 2(62) (Irkutsk: Publishers of Irkutsk National Research Technical University)