**Adaptive Control Method for Parallel-Operating   
Four-Quadrant Converters of an Asynchronous Electric Drive of an Alternating Current Electric Locomotive**

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**Abstract.** A method for controlling the asynchronous electric drive of an alternating current electric locomotive using parallel-operating four-quadrant converters (4QS) is presented. The novelty lies in the introduction of an adaptive frequency multiplicity of PIM depending on the traction load, which allows for the improvement of energy characteristics, including efficiency and power factor. Modeling based on Matlab Simulink was carried out, confirming an increase in efficiency up to 2-2.5% compared to existing methods.

**Key words:** four-quadrant converters, asynchronous electric drive, electric locomotive, pulse width modulation, energy efficiency, parallel-operating, power factor, Matlab Simulink

**INTRODUCTION**

Improving energy efficiency remains a key challenge in modern traction electric drives of AC electric locomotives, particularly when using asynchronous motors and input power converters. The use of four-quadrant converters enables the implementation of regenerative braking and controlled startup. However, most existing control methods rely on a fixed modulation frequency, which reduces efficiency under variable load conditions [7, 8, 9, 10].

In addition, the lack of adaptability in modulation strategies leads to suboptimal switching of power semiconductor devices, resulting in increased switching losses and electromagnetic interference. This is especially critical in heavy-haul electric locomotives, where traction load conditions vary significantly during operation due to track profile, speed fluctuations, and operational constraints. Therefore, there is a strong need for control methods that dynamically adjust to real-time load conditions, improving overall system efficiency and ensuring stable power quality across a wide range of operating modes.

**REVIEW OF EXISTING METHODS AND THEIR LIMITATIONS**

One of the established methods for controlling a four-quadrant converter (4QS) involves regulating the current of the variable electromotive force (EMF) source by adjusting the duration of voltage application and the voltage difference between the source and the output filter capacitor [1]. For this purpose, the half-period of the supply voltage is divided into *m* equal intervals, and in each interval, the reference value of the current is calculated according to a sinusoidal law. During the control process, a continuous comparison between the actual current and the reference current is performed, and based on this comparison, the structure of the applied voltage is modified.

The main disadvantage of this method is that it controls a single converter using a fixed pulse-width modulation (PWM) frequency multiplicity, without accounting for variations in the traction load. This limits the flexibility of the control system and reduces its energy performance, especially under variable operating conditions of the electric locomotive.

A more advanced approach is the control method for the parallel operation of four-quadrant converters [2]. In this method, the generation of control pulses is based on the duty cycle function of pulse-width modulation (PWM), with each converter assigned a fixed phase shift. The sequence of phase shifts is organized in such a way as to alternate positive and negative values relative to the first (zero) converter, which contributes to the reduction of harmonics in the power supply network.

The disadvantages of this method include the lack of consideration for load current and voltage during the formation of control actions, a fixed PWM frequency without adaptation to actual operating conditions, increased complexity of the control scheme as the number of parallel converters grows, and potential degradation of coordination between converters under varying load conditions.

Thus, the analyzed methods do not provide dynamic adaptation of the modulation frequency to variations in the operational parameters of the traction load, which represents a fundamental limitation in the pursuit of improved energy efficiency.

**JUSTIFICATION AND PROBLEM STATEMENT**

The stated problem is addressed by a control method for the parallel operation of four-quadrant converters, in which the switching of power semiconductor devices in the phase modules of the converters is carried out based on the duty cycle function of voltage pulse-width modulation (PWM), with each converter controlled using a fixed modulation phase shift. The number of converters operating in parallel is defined, and an odd number of PWM voltage pulses is applied to the input of each converter during one half-period of the carrier frequency. The phase shift of each converter is arranged so that the first converter operates with zero phase shift of the grid current, and each subsequent (even-numbered) converter operates with a positive phase shift relative to the first [3, 4, 5].

New control features are introduced - specifically, the modulation frequency multiplicity with respect to the harmonic content and the relative traction load coefficient of the electric locomotive. Based on these, the power factor and efficiency of the four-quadrant converters are determined, taking into account the locomotive load.



**FIGURE 1.** Block diagram of a dual-loop control system for 4QS converters implementing the proposed control method

**CONCEPT OF THE PROPOSED METHOD**

The method for controlling the parallel operation of four-quadrant converters is implemented using a microprocessor-based system (Figure 2), which consists of a group of current sensors 1 (11, 12, ..., 1N) and a group of voltage sensors 2 (21, 22, ..., 2N), a driver block 3 (31, 32, ..., 3N), power switches of a group of parallel-connected four-quadrant converters 4, consisting of N converters (41, 42, ..., 4N) supplied by alternating voltage *u*, a synchronization block 5 that synchronizes converters 4 with the power source, a processor 6, a random-access memory (RAM) unit 7, a read-only memory (ROM) unit 8, a timer block 9, an analog-to-digital converter (ADC) 10, a pulse-width modulation (PWM) block 11, an input/output (I/O) block 12 for defining the timing intervals of control signals, a computation block 13, an interrupt controller 14, a capture/compare module 15, a transformer 17, a proportional-integral (PI) block 18, a timing voltage block 19, and a reference-setting block 20.

The signal, after undergoing phase shift formation, is processed according to a proportional-integral law, multiplied by the signal received from the reference-setting block, which defines the voltage value in the DC-link, and then transmitted to the capture/compare module 15, from which it is delivered to the corresponding converters 4. The signals measured by the current and voltage sensors at the output of converter 4 are sent to the PWM block 11 and then transmitted to the timing voltage block 18. Depending on the number of active four-quadrant converters (4QS), the control system adjusts the phase of the timing voltage. The inputs and outputs of the synchronization block 5, processor 6, RAM unit 7, ROM unit 8, timer block 9, ADC 10, and the inputs of the driver block 3 are interconnected via a data-address bus 16. The converters 4 are powered by a single-phase AC power supply, the voltage of which is supplied to the input of the synchronization block 5.

The output of the synchronization block is connected to the synchronization buses of the processor 6, RAM unit 7, ROM unit 8, and ADC 10. The current values of the supply current and voltage are fed to the input of the ADC 10. The processor 6, RAM unit 7, ROM unit 8, timer block 9, ADC 10, PWM block 11, I/O block for timing intervals of control signals 12, computation block 13, interrupt controller 14, and the capture/compare module 15 can be implemented on the basis of the M167-1x microcontroller (product catalog of JSC “KASKOD”, "Onboard and Industrial Electronics", 189625, St. Petersburg, Pavlovsk, Filtrovskoye Highway, 3, tel. +7 (812) 466-5784, +7 (812) 476-0795, p. 66).

**CONTROL ALGORITHM**

The control method for the parallel operation of four-quadrant converters is implemented according to the algorithm shown in figure 2 (the block numbers in the algorithm diagram continue the numbering from the block diagram).

In block 21, the number of parallel-operating converters *N* is set, as well as the number of PWM voltage pulses applied to the input of each four-quadrant converter during one half-period of the supply voltage, corresponding to the duty cycle function of pulse-width modulation. The relative traction load coefficient is also entered.

The system checks the condition for adjusting the modulation frequency multiplicity of PWM triggering signals for converters 41...4N depending on changes in the locomotive load and determines the appropriate frequency value at the input of each converter. In blocks 22, 24, and 26, the system checks and identifies the modulation frequency multiplicity at which each converter is operating, and performs the corresponding efficiency calculations (23, 25, 27, 28) according to formula (1).

**MATHEMATICAL MODELING**

Efficiency Calculation:

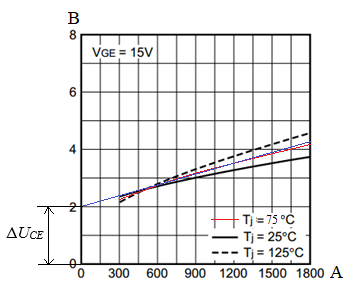
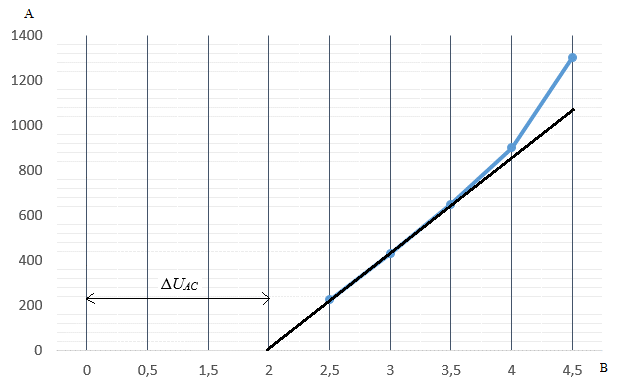
(1)

where, Pd – output power of the 4QS converter; k – load variation coefficient of the 4QS converter in relative units (0.75; 1; 1.25); E(n)ts – energy loss in the transistor switch during the *n*-th switching interval; E(n)d – energy loss in the diode within the transistor switch circuit during the *n*-th switching interval; E(n+1)df– energy loss in the diode group during the *(n+1)*-th interval of energy transfer to the filter; fc ​ – frequency of the converted multiplicity [6, 7, 8].

To solve equation (1), certain parameters were taken from the volt-ampere characteristic (Figure 3 а and b) [9].



**FIGURE 2.** Algorithm for implementing the proposed method for controlling parallel operation of four-quadrant converters



**FIGURE 3.** Volt-ampere characteristics of the transistor module of the MG900GXH1US5 series (a) and the diode (b)

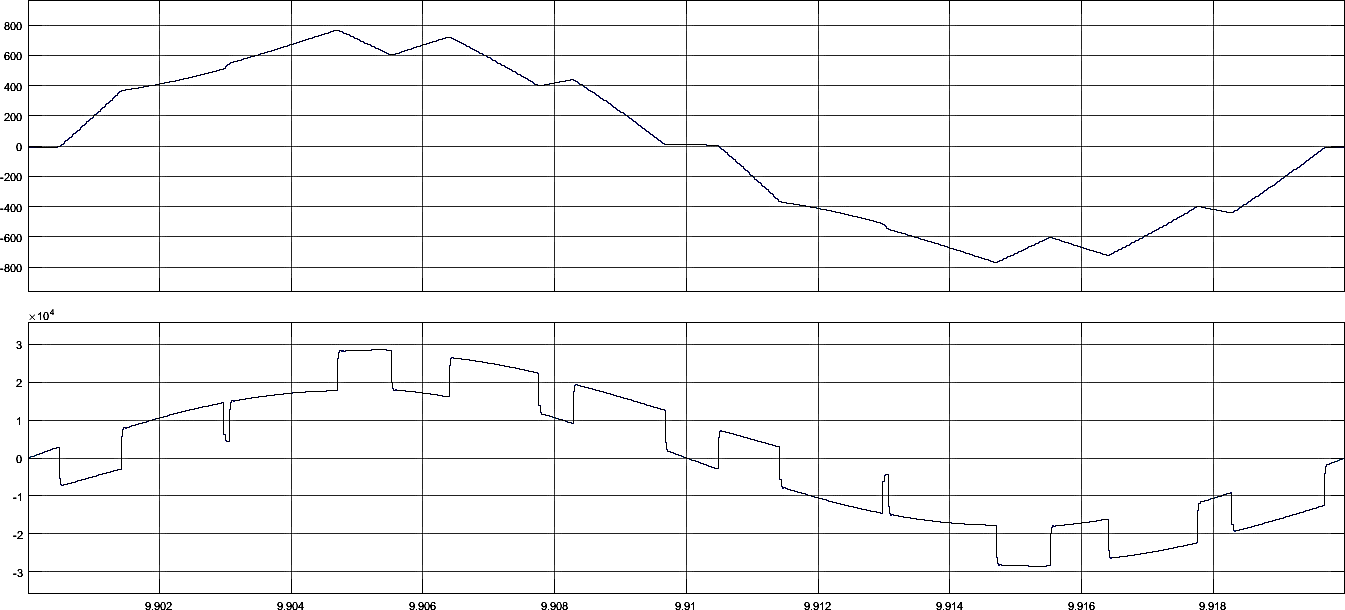
Power Factor Calculation:

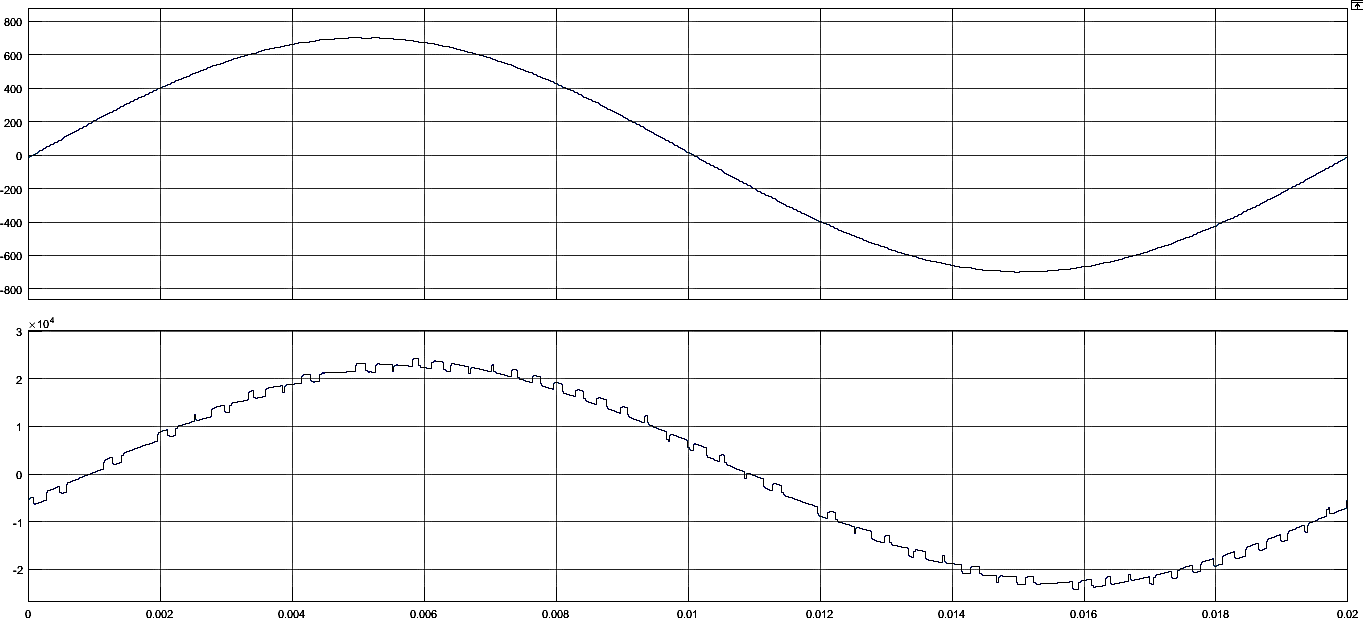
(2)

where Ieff and Ueff are the effective values of current and voltage at the input of the traction transformer; Im and Um are the average values of current and voltage at the output of the intermediate DC-link; φ is the phase angle of the fundamental harmonic of the current relative to the fundamental harmonic of the voltage at the input of the network winding of the transformer; N is the number of 4QS of the electric locomotive operating in parallel.

In block 29, the maximum values of the energy-efficiency indicators of the converter are selected, and in block 30, the results are output. From figure 4 and figure 5, it can be seen that the energy-efficiency indicators of the converter are improved by changing the multiplicity of the PWM triggering signals depending on the load.

The proposed control method for the parallel operation of four-quadrant converters improves the quality of the current consumed by the electric rolling stock. Specifically, it reduces the amplitude of high-frequency current ripple in the electric locomotive, thereby enhancing the energy performance and electromagnetic compatibility of the traction drive system [10, 11, 12]. In Figure 4 (a and b), the time-domain waveforms of the currents of the four-quadrant converters and the locomotive current are presented — both before applying the proposed method and after, i.e., under the condition of parallel operation of two 4QS units with a modulation frequency of 250 Hz for each converter (corresponding to 5 pulses per half-cycle of the industrial frequency).

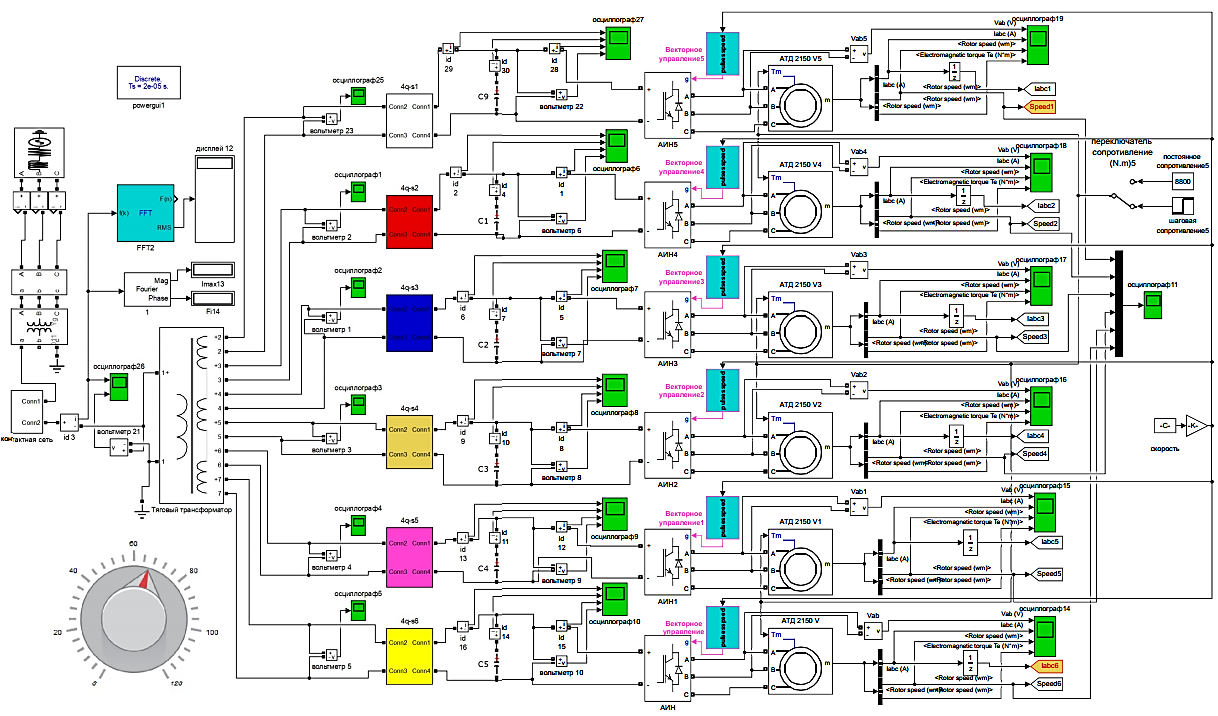
a)

b)

**FIGURE 4.** The time-domain waveforms of the currents of the four-quadrant converters

Thus, the set of features newly introduced in the proposed control method makes it possible to solve the problem addressed by the invention, thereby ensuring the achievement of the desired technical result [13, 14, 15, 16].

**COMPUTER MODEL OF THE PROPOSED METHOD**

To analyze the power circuit, the Matlab software package was used. The Simulink tool, which includes a library of components for the electric locomotive power circuit—specifically, blocks representing the four-quadrant converters (4QS) of asynchronous traction motors (ATM) and other elements necessary for building the circuit—was employed (Figure 4). For simulating the converters, universal converter blocks were used. The parameters were assigned according to the specifications of modern locomotives. The DC circuit elements (inserts) were also configured in accordance with the characteristics of electric locomotives [17, 18].

**FIGURE 5.** Computer model of the power supply circuit for the asynchronous traction motor (ATM) of one section of the   
"O‘Z-ELR" electric locomotive

The calculations were performed at a feeder voltage of 27 kV from the traction substation and at the maximum distance (20 km) from the substation, which corresponds to the equivalent electrical resistance of the catenary for that distance. The DC-link voltage was assumed to be Um=3000 V Um=3000V. The load on the asynchronous traction motor (ATM) was varied in the range from 0.75Um​ to 1.25Ud at nominal stator voltage frequencies of 46 Hz and 60 Hz. The multiplicity factor of the PWM control signals of the 4QS converter, PWM​ was varied from 5 to 10.

A study was conducted on the influence of mutual phase shift and the multiplicity of the PWM triggering frequency of parallel-operating four-quadrant converters (4QS) on the power factor (χ) and the conversion efficiency (η) of the 4QS converters.

**RESEARCH RESULTS**

According to the calculations obtained from the computer model of the proposed method, a table was compiled (Table 1) containing the numerical values. Based on these values, graphical illustrations were created (Figures 6 and 7), clearly demonstrating the changes in the energy performance indicators of the four-quadrant converter, which significantly contribute to improving the energy efficiency of the entire asynchronous electric drive system of AC electric locomotives.

The dependence of the efficiency and power factor of the parallel-operating converters, shown in figures 6 and 7, as the traction load power varies, demonstrates a gradient intensity of approximately 0.01 as the traction load increases from 0.75 P to 1.25 P, primarily due to increased losses in the reverse diodes of the inverter circuit.

**TABLE 1.**

| **Relative Load** | **Efficiency η (existing method)** | **Power Factor χ (existing method)** | **Efficiency η (proposed method)** | **Power Factor χ (proposed method)** |
| --- | --- | --- | --- | --- |
| 0.75 | 0.983 | 0.957 | 0.987 | 0.981 |
| 1.00 | 0.980 | 0.962 | 0.989 | 0.981 |
| 1.25 | 0.981 | 0.956 | 0.991 | 0.960 |

**FIGURE 6.** Comparison of the efficiency (η) versus traction load for the existing and the proposed control methods

**FIGURE 7.** Comparison of the power factor (χ) versus traction load for the existing and the proposed control methods

**CONCLUSIONS**

Therefore, the control approach that is offered to regulate parallel operation of four-quadrant converters improves the quality of current that the electric rolling stock consumes. It can decrease high frequency current ripples amplitude in the locomotive, enhance energy efficiency of the system, and enhance electromagnetic compatibility of the traction drive. The gist of the approach is the use of the adaptive frequency multiplicity of PWM triggering signals so that the operating regimes of the converters could be dynamically changed in dependence on traction load variations.

This not only allows the most favorable switching conditions on power semiconductors, but also actually lowers the overall energy losses in transistors and diodes (especially where the load varies). The effectiveness of the proposed method was also confirmed by computer modeling conducted in the Matlab Simulink environment. Based on the simulation output the converter system was more efficient (improved by up to 2 - 2.5 per cent) as compared to existing techniques with the same power factor (staying higher over the entire load range). Another strength of the approach is that it scales with more and more parallel converters, so it is applicable to contemporary high-power electric locomotives.

The suggested scheme as applied to the digital control systems could be applied by using microprocessor-based digital technologies as DSPs and FPGAs with the certainty of its realization. Overall, the package of new features added to the control system of four-quadrant converters manages to tackle the problem of enhancing the energy efficiency of the traction electric drive of alternating current electric locomotives and will help in the attainment of the technical outcome.

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