Parallel operation of an inverter with an electrical AC network

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Abstract. The paper studies the matters of the interaction of a source of non-sinusoidal current and voltage with a centralized power supply system for the electric energy recuperation during electric braking of rolling stock on the railroads. Revised energy conservation law in electromagnetic field and spectral analysis of non-sinusoidal voltage and current at the output of the inverter have been used to prove the cause of reduced current of RMS voltage in the overhead system. It has been calculated that controlling the active power of recuperation due to the phase shift of the harmonic current components relative to the similar harmonic voltage components is accompanied by a significant increase in the reactive component of the surge current compared to its active component. Losses of active power in the electric stock recuperating heat exchanger make up 83–87 % of the total power loss in the recuperating heat exchanger and in the overhead system. The reactive component of the equalizing current loads the transformers of the traction substations, therefore the voltage on the buses of the substation switchgear decreases. It is proposed to increase the voltage of the overhead system and the traction substation during the recuperation to maintain the minimum phase shift angle of the harmonic components of the non-sinusoidal current relative to the similar harmonic components in the overhead system.

1. Introduction

The most important factor in reducing the cost of the energy component of material production in the state economy sectors and mitigating the negative impact of energy on the environment is energy saving and power-efficient use of electric energy [1, 2]. During transport operations, significant savings in electric energy consumption for train traction are possible due to the use of potential and kinetic energy of a train. The volume of regenerative braking in the railway network reaches 2.151 billion kWh, which is about 5 % of the train traction consumption [3, 4]. Currently, due to the potential and kinetic energy of the train, energy recuperation is performed by inverters controlled by an AC network and four-quadrant 4-qS converters, whose power factor decreases to 0.5 and the efficiency goes down to 70 % [5, 6].

The losses of active power with the electric energy recuperation from the AC generators of the electric stock (ES) into the system of external power supply in the electric stock reversible converter comprise 83 – 87 %, and in the overhead system of electric transport power line comprises 13–17 % from the total losses of active power in the traction transformer, reversible converter of electric stock and in the overhead system [7–9]. Due to the decrease in the RMS voltage in the AC overhead system and on the buses of the traction substation during operation of known recuperating heat exchangers, the track capacity of railway sections in mountainous and hilly areas is reduced [10, 11]. The aim of this
work is to increase the productivity of railways and to reduce energy consumption for train traction through the use of power-efficient recuperation of electric energy by traction rolling stock.

2. Subject of research and methods
During electrical energy recuperation, limited-power electric stock DC generators interact with traction transformer substations. The shape of the AC voltage curve on their buses is close to sinusoidal. The interaction is carried out through inverters and an overhead network with real and inductive resistance. Reversible converters (RCs) form rectangular alternating current, and 4qS-converters form pulse current, whose envelope is close to sinusoidal form. The power at the output of the inverter is controlled by shifting the rectangular current in phase to the advance side with respect to the voltage in the secondary winding of the ES traction transformer from the minimum advance angle of the inverter thyristors to π/2. In the overhead system, the reactive component of the rectangular equalizing current increases and significantly exceeds the active component of the reactive current, and energy recuperation stops at π/2. With a pulsed form of current at the output of the inverter, during the pause between pulses, the electric potential of energy sources is not used for recuperation.

For the studies, the refined energy conservation law and new energy characteristics [12] of alternating current energy generators of limited power are used in parallel with the traction transformer substation, which is powered from a centralized energy system. Computer-based mathematical modeling, spectral analysis of non-sinusoidal voltage and current at the inverter output are used to estimate the energy efficiency of parallel operation of the inverter with the AC system.

3. Research method
The power balance at the output of the heat exchanger [13], taking into account the reduction in the duration of the irreversible conversion of electrical energy into a different type of energy by reactive elements and power semiconductors of the recuperating heat exchanger (1):

\[ \sqrt{S_G^2 - \Delta S^2} = \sqrt{P^2 + Q^2}, \]  

(1)

where ΔS is a part of the apparent power \( S_G \), at the output of the recuperative heat exchanger, which is not used for recuperation of electrical energy and for energy exchange in the electrical circuit; 
\( P \) is the total active power of the harmonic components of voltage and current at the output of the recuperating heat exchanger; 
\( Q \) is the total reactive power of the harmonic components of voltage and current at the recuperating heat exchanger output.

The components of the proposed power balance (1) can be calculated and measured using Fourier transform, analytical calculations, mathematical modeling and instrumentation equipment in actual practice.

Let us calculate the power ΔS, which is formed at the output of the recuperating heat exchanger, and which takes into account the electric potential of the energy source while switching the power semiconductors of the inverter:

\[ \Delta S = \sqrt{\sum_{k=0}^{n} U_{pk}^2 \cdot I_k^2} = U_P \cdot I_{in}, \]  

(2)

where \( U_{pk} \) is the RMS voltage of the k-th harmonic component at the output of the recuperating heat exchanger while switching the power semiconductors of the inverter; 
\( I_k \) is the RMS current of the k-th harmonic component at the recuperating heat exchanger output; 
k is the number of the harmonic component; 
n is the number of the last harmonic taken into account; 
where \( U_P \) is the RMS voltage at the output of the recuperating heat exchanger while switching the power semiconductors of the inverter;
\( I_{fo} \) is the RMS current at the recuperating heat exchanger output.

Active power at the recuperating heat exchanger output characterizes a part of electrical energy, which is irreversibly transformed into another type of energy, into thermal energy losses in a power circuit, and is transferred to an external power supply system:

\[
P = U_{c0} \cdot I_0 + \sum_{k=1}^{n} U_{ck} \cdot I_k \cdot \cos \varphi_k,
\]

where \( U_{c0} \) is the constant component of the voltage at the recuperative heat exchanger output during the transfer of energy to the AC network;

\( U_{ck} \) is the RMS voltage of the \( k \)-th harmonic component at the recuperative heat exchanger output during the transfer of energy to the AC network;

where \( U_0 \) is the constant component of the current at the recuperative heat exchanger output during the transfer of energy to the AC network;

\( \varphi_k \) is the phase angle of the \( k \)-th current harmonic relative to the similar \( k \)-th voltage harmonic at the recuperating heat exchanger output.

Reactive power at the recuperative heat exchanger output, which characterizes a part of the electrical energy consumed for energy exchange between the energy source and reactive elements of the electric circuit, is:

\[
Q = \pm \sqrt{\sum_{k=1}^{n} U_{ck}^2 \cdot I_k^2 \cdot \sin^2 \varphi_k},
\]

The angle of apparent power and output electrical resistance \( \varphi \) of the recuperating heat exchanger is:

\[
\varphi_{\Sigma} = \arctg \left[ \pm \frac{\sqrt{\sum_{k=1}^{n} U_{ck}^2 \cdot I_k^2 \cdot \sin^2 \varphi_k}}{U_{c0} \cdot I_0 + \sum_{k=1}^{n} U_{ck} \cdot I_k \cdot \cos \varphi_k} \right],
\]

Using expressions (1–5) and mathematical modeling in the Simulink environment of the MATLAB software, it is possible to obtain an estimate of the energy efficiency of the electrical energy recuperation process.

When the reversible converter operates in the mode of 2ESSK electric locomotive inverter in the middle of an inter-substation area with duplicate power supply to the overhead system and the advance angle of the inverter thyristors increases up to \( \beta = 72 \) electrical degrees in order to increase the transfer of active power to the external power supply system, a mathematical model of the recuperation process is shown in Figure 1. The mathematical model of a traction transformer substation is presented using an EMF source of 27 500 V with internal resistance and inductance. The overhead system with duplicate power supply 2 has a resistance of 2.5 Ohms and an inductance of 16 mH. Traction transformers of two-section EMF with a rated power of 4350 kVA, rated voltage in the primary winding of 25 kV have 3 sections of consecutively connected secondary windings. The source of DC energy is a DC EMF with real and inductive resistances.

Active power at the recuperating heat exchanger input \( P_d = U^{dc} \cdot I_d = 900 \cdot 8375 = 7537.5 \) kW is calculated using readings of the instruments in figure 1 for measuring voltage \( U^{dc} \) and the RMS current in the windings of electric machines \( I_d \). The oscillogram of the curves of instantaneous values of voltage and current in the primary and secondary windings of the ES traction transformer is shown in Figure 2. The oscilloscope and powerqui block in Figure 1 allow one to perform calculations of the harmonic components of non-sinusoidal voltage, equalizing current and power balance components at the output of the ES recuperating heat exchanger.
Figure 1. The mathematical model of the process of electrical energy recuperation.

Figure 2. Oscillograms of voltage $U_1$, current $I_1$ in the primary and $U_2$, $I_2$ in the secondary winding of the traction transformer when the reversible converter is operating in the electric energy recuperation mode.

As a result of the spectral analysis of non-sinusoidal curves $U_i$ and $I_i$, the values and initial phases of the similar harmonic components are obtained in Figure 3.
Figure 3. The results of the spectral analysis of periodic functions $U_1$ and $I_1$.

The RMS value of the voltage of the first harmonic is $U_{1(1)} = 25100$ V, $f_1 = 50$ Hz, the RMS value of the current of the first harmonic is $I_{1(1)} = 380.5$ A, $f_1 = 50$ Hz.

According to the formula (3), the active power is calculated taking into account the phase angle of the similar harmonic components with respect to voltage

$$ P_1 = U_{1(1)} \cdot I_{1(1)} \cdot \cos (4.9^{\circ} - 239.4^{\circ}) = -5546.03 \text{ kW}, \quad P_3 = -33.45 \text{ kW}, \quad P_5 = -9.92 \text{ kW}, \quad P_9 = -0.99 \text{ kW}, \quad P_{11} = -0.10 \text{ kW}, \quad P_{13} = +0.05 \text{ kW}, \quad P_{15} = -0.05 \text{ kW}, \quad P_{17} = -0.16 \text{ kW}, \quad P_{19} = -0.18 \text{ kW} $$

and the total active power of the harmonic components taken into account is

$$ P = -5594.6 \text{ kW}. $$

The error of calculation and mathematical modeling is 0.8%.

According to the formula (4) the reactive power at the output of the inverter of the electric locomotive is

$$ Q_1 = U_{1(1)} \cdot I_{1(1)} \cdot \sin (4.9^{\circ} - 239.4^{\circ}) = -7775.25 \text{ kVAr}, \quad Q_3 = -335.12 \text{ kVAr}, \quad Q_5 = -145.65 \text{ kVAr}, \quad Q_7 = -61.68 \text{ kVAr}, \quad Q_9 = -21.0 \text{ kVAr}, \quad Q_{11} = -4.53 \text{ kVAr}, \quad Q_{13} = -0.46 \text{ kVAr}, \quad Q_{15} = -1.30 \text{ kVAr}, \quad Q_{17} = -2.65 \text{ kVAr}, \quad Q_{19} = -2.81 \text{ kVAr}. $$

The total reactive power of the harmonic components taken into account is

$$ Q = -7784.11 \text{ kVAr}. $$

Using the device $P$, $Q$ in Figure 1, the reactive power $Q = 7771.0 \text{ kVAr}$ of the first harmonic of voltage $U_{1(1)}$ and current $I_{1(1)}$ was measured.

With the help of formula (5) one can calculate the angle of apparent power, the output electrical resistance of the inverter with electric ES machines

$$ \phi_{\sum} = \arctg \left( \frac{-7784.11}{-5594.60} \right) = 54.29^{\circ} $$

which is indicative of the active and real nature of the output electrical resistance of the inverter with electric machines of electric stock. The apparent power at the ES current collector is

$$ S = U_{tp} \cdot I_{tp} = 25590 \cdot 402.1 = 10289.74 \text{ kVA}. $$

The power at the current collector during the switching of the inverter thyristors is

$$ \Delta S = \Delta U \cdot I_{tp} = 9007 \cdot 402.1 = 3621.71 \text{ kVA}. $$

The power factor of reversible converter in the recovery mode

$$ K_M = P / S = 5594.6 / 10289.74 = 0.54. $$

The efficiency of reversible converter when operating in the recovery mode is:

$$ \eta_{RC} = (P / P_d) \cdot 100 \% = (5594.6 / 7537.5) \cdot 100 \% = 74.2 \%. $$

The power balance (1) is checked at the output of the electric energy recuperating heat exchanger of electric stock and the calculation error is determined as:

$$ S_d^0 - \Delta S^2 = \sqrt{P^2 + Q^2}; \quad \sqrt{10289.74^2 - 3621.71^2} = \sqrt{5594.6^2 + 7784.11^2}. $$

9631.3 kVA ≈ 9586.0 kVA, the calculation error is 0.5%.
Active power losses in the AC overhead system with duplicate power supply with active resistance $R_{os} = 2.5$ Ohm is:

$$\Delta P_{os} = I_{tp}^2 \cdot R_{os} = 402.1^2 \cdot 2.5 = 404.2 \text{ kW}.$$  

Losses of active power in the overhead system make up 17%, and in the reversible converter of the electric stock they make up 83% of the total losses of active power in the overhead system and in the reversible converter of the electric stock.

Active power transmitted to the external power supply system is:

$$P\cdot \Delta P_{os} = 5594.6 \cdot 404.2 = 2190.4 \text{ kW}.\]

In the ES current collector during the energy recuperation, the voltage is less than the voltage at the traction substation and is 25590 V. The voltage on the buses of the traction substation is 26270 V, that is, deviates by -0.95% from the set voltage when the substation transformer is idle. The sinusoidal distortion of the voltage curve is $U_{f}$ $K_{U} = 20.0$ % and in the overhead system is estimated using the instrument Total Harmonic Distortion (THD) in Figure 1 during the inverter operation.

4. Conclusion

As a result of the study, it was found that the voltage in the overhead system decreased during the recuperation of electrical energy. Nonlinear distortion of the sinusoidal voltage curve in the overhead system reaches 8–20%. Losses of active power in the traction transformer and reversible converter make up 83–87%, and losses of active power in the overhead system make up 17% of the total losses of active power in the traction transformer, reversible converter of electric stock and in the overhead network. Due to the phase shift of the non-sinusoidal voltage at the inverter output by the ES thyristors relative to the alternating voltage on the buses of the traction substation, a non-sinusoidal equalizing current is formed in the electrical circuit.

The reactive component of the equalizing current significantly exceeds the active component of the equalizing current in magnitude with an increase in the inverter thyristors turn-on advance angle to $\beta = \pi/2$. Therefore, the reactive power consumed from the traction substation exceeds the active power at the output of the electric stock inverter. Due to the reactive component of the non-sinusoidal equalizing current, the active power loss in the reversible converter and in the overhead system increases with increasing advance angle of the inverter thyristors. The switching of a high equalizing current by the thyristors of the reversible converters limits the minimum advance angle of the inverter thyristors to $\beta = 36$ electrical degrees due to the increased probability of the inverter triggering. When the advance angle of the inverter thyristors $\beta = \pi/2$, energy recovery stops, as the reversible converter switches from the inverter operation mode to the rectifier operation mode. When $\beta \geq \pi / 2$, the offset angle of the harmonic components of the equalizing current increases relative to the similar harmonics of the alternating voltage in the overhead system, therefore, electric energy is consumed from the overhead system to create the braking force of the electric stock.

The calculation results confirm the relevance of the development and application of technical solutions that reduce active power losses, increase the RMS voltage in the AC overhead system during the recuperation of electrical energy into the external power supply system.

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