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# ANALYSIS OF THE IMPACT OF ELECTRIC LOCOMOTIVES ON ENERGY PARAMETERS IN THE POWER SUPPLY SYSTEM

Dragutin KOSTIĆ[1]
Petar MARKOVIĆ[2]

***Abstract*** *– Electric locomotives and electromotive trains in service on the networks of electrified railways of Serbia have a technological level, equipment for electricity conversion which covers the spectrum from the sixties of the last century to modern advanced solutions of traction and electric braking systems. The paper analyzes the feedback effects of the locomotive on the network as a generator of current harmonics, and qualitative parameters of power that the locomotive takes from the network for the cases of the diode and thyristor locomotives that are most represented in traffic and modern locomotives with four-quadrant converters and asynchronous traction motors. The results of the analysis indicate that the owner of the infrastructure within the calculation of prices has the possibility to classify the rolling stock according to type according to the impact these on the supplying network*

***Keywords – Electrical Locomotives, Power factor, Power Supply System***

## 1. INTRODUCTION

It is known that electric locomotives are nonlinear electric loads. This is a consequence of the conversion of electricity starting from the point of collection, at the connection of the pantograph with the contact wire, to the connections of the traction motors. This has the consequence that the estimate of electricity consumption based on expression (1) cannot be taken as credible because the linear relations of simple periodic currents and voltages on the alternating side do not represent an adequate and realistic state.

$$W(NT) = U_{\max} I_{\max} \sum_{k=1}^{N} \int_{(k-1)T}^{kT} \cos\omega t \ \cos(\omega t - \varphi)\, dt \qquad (1)$$

The nonlinearity of the load is manifested by the appearance of harmonic currents in line, generated by converters that affect the quality of electrical power. Several IEEE and IEC standards address power quality issues. Distorted current in the contact network with negligible inductance leads to voltage distortion, which can have negative effects on consumers sensitive to voltage or current distortion. Also, higher harmonics of currents in the network cause additional losses that are impossible to measure on the measuring devices on the locomotive that provide data on the taken active power. Fortunately, depending on the type of converter that causes complex periodic currents in the contact network, it is possible to evaluate this element of the impact of the electric locomotive on the power supply network. It is necessary to define the appropriate criteria and their quantitative value that would provide insight into the process of distortion of the power supply network parameters. In defining the criteria, we will assume that the voltage in the contact network is with negligible distortion, so its RMS value is approximated by the RMS value of the fundamental harmonic. As the current in the network is a complex periodic, expression for its current value is:

$$i(t) = \sum_{n=1}^{\infty} \sqrt{2} I_n \cos(n\omega t - \varphi_n) \qquad (2)$$

The current distortion factor is defined by the following expression:

$$DF_i = \frac{I_1}{\sqrt{\sum_{n=1}^{\infty} I_n^2}} \qquad (3)$$

From expression (3) the total current distortion concerning the sinusoidal wave is:

$$THD = \sqrt{\left(\frac{1}{DF_i}\right)^2 - 1} \qquad (4)$$

[1] University of Belgrade, Faculty of Transport and Traffic Engineering, Vojvode Stepe 305, Belgrade, Serbia, d.kostic@sf.bg.ac.rs
[2] University of Belgrade, Faculty of Transport and Traffic Engineering, Vojvode Stepe 305, Belgrade, Serbia, p.markovic@sf.bg.ac.rs

Quantitative indicator of the influence of electric locomotive on the primary network is determined by the power factor PF which is defined by:

$$PF = \frac{UI_1 \cos\varphi}{U\sqrt{\sum_{n=1}^{\infty} I_n^2}} = DF_i \cos\varphi \qquad (5)$$

## 2. REVIEW OF POWER ELECTRONICS TECHNOLOGIES FOR LOCOMOTIVES

Diode locomotives belong to the technological generation of the 1960s, but they still make up the majority of the fleet of domestic operators represented through series 441 and 461. Their typical structure of the traction circuit allows an identical approach to be applied for both series. The basic parameters that determine the waveform of the current in the primary network are the reactors in the traction motor circuit, the counter-electric motor force of the rotor, and the commutation of the rectifying diodes in the bridge. Thyristor locomotives are equiped with fixed turns ratio transformers. Regulation of the traction parameters is performed through control of the assymetric thyristor bridges. Thyristor locomotives, that operate in the Serbian railway network, belong to series 444. They were result of modernisation and modification of the diode four-axle locomotives, from series 441. Recently, locomotives with asynchronous traction motors are procured. They represent modern traction vehicles, with dominant technological features comparing to previously existing traction vehicles. This paper presents an analysis of the impact of the three main locomotive types on the power parameters of the catenary supply network, with power factor as main quantitve criterion.

### 2.1. Locomotive with diode rectifier

A very simplified approach that takes into account only the inductance of the reactor and neglects the commutation and resistance in the traction motor circuit leads to the assessment that alternating current consists of rectangular half-cycles of intensity $I_M$. In this case $DF_i$=0.9 and $THD$=0.4843. In this simplified case, the maximum value of the power factor is $PF$=0.9 with cos$\varphi$=1.

To obtain the dependence of the power factor as a function of the active power of the locomotive in the range between (10% -100%)$\boldsymbol{P_n}$ we use the simulation approach. In this manuscript, the SIMULINK simulation package or its toolbox “SIMSCAPE POWER SYSTEMS” was used. The simulation model of the traction circuit (Fig. 1) aims to provide insight in the real forms of current in an alternating circuit that is connected via a diode rectifier to a traction motor that is modeled as an RLE circuit.

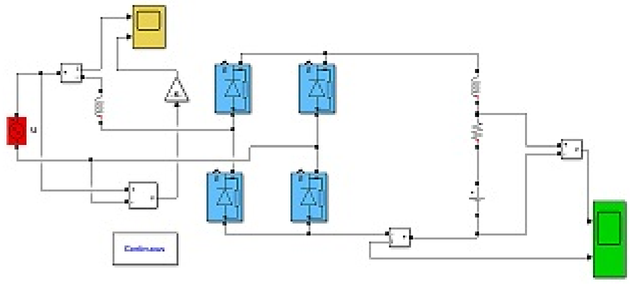

*Fig. 1. Simulation model of the converter with diode rectifier*

From the diagram in Fig. 2, the real waveform of the current has the characteristic slope at the change of polarity and upper and lower waveform which is a consequence of the size of the inductor in the traction motor circuit. By varying the voltage and the counter electromotive force up to the value corresponding to the maximum speed on the simulation model, the function is obtained:

$$PF = f\left(\frac{P}{P_{\max}}\right) \qquad (6)$$


*Fig. 2. Current waveform (red) in the AC terminal of the diode rectifier*

### 2.2 Locomotive with thyristor rectifier

The development of power electronics has led to the use of thyristors or controllable rectifiers with phase control with symmetrical or asymmetrical bridge topologies

Thyristorised locomotives were created by the modernization of diode locomotives so that voltage control on the traction motor is achieved by changing the angle of the deblocking of the thyristor in the asymmetric bridge when it consists of two diodes and two thyristors. The average value of the DC voltage is a function of the amplitude of the input alternating voltage and the angle that controls the switching on of the thyristors. Although this solution has a clear advantage in terms of continuity of locomotive traction control, deteriorations in the alternating circuit are noticeable, which are quantified through the worsened power factor.

Figure 3 shows a simulation model with clearly highlighted circuits for controlling the thyristor deblocking angle and a traction energy circuit. The voltage and current characteristics on the DC and AC sides are graphically displayed using modeled oscilloscopes. Also, numerical data for determining the functional dependence are specially stored and processed in MATLAB.

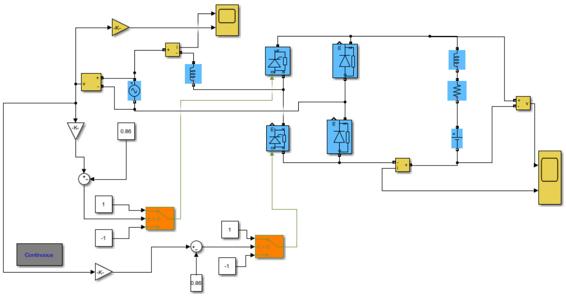

*Fig. 3. Simulation model of the converter with asymmetric thyristor bridge*

From the diagram of voltage and current (Fig. 4) on an AC side, the phase shift of alternating current to the voltage affects the increased delay of the fundamental harmonic of current or to the decrease of cos$\varphi$ in relation to the phase shift of the fundamental harmonic of current to the voltage in the diode locomotive.

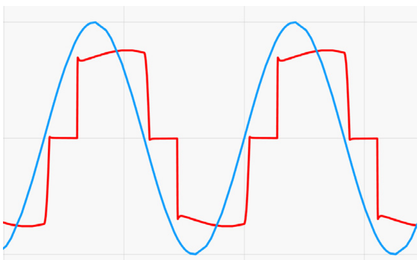

*Fig. 4. Current waveform (red) on the AC side of the asymmetric thyristor bridge*

### 2.3. Locomotive with four-quadrant converter and asynchronous traction motors

When undulated DC traction motors were replaced by three-phase asynchronous motors, the first solutions of AC/DC converters were based on symmetrical or asymmetric thyristor converters Such solutions have further increased the disadvantages related to the poor power factor and the distortion factor of alternating current, which is a measure of the deviation of the shape of alternating current from the ideal sinusoid.

These shortcomings were especially evident in the mass use of power locomotives in between (5-6 MW) because the impact on the catenary is very pronounced. Another important drawback was related to regenerative braking, which is impossible in the case of an asymmetric thyristor bridge. By applying asymmetrical thyristor bridge, the generated electric power due to recuperation was highly distorted in comparison to the power with sinusoidal values of current and voltage.

Four static switches T1…T4 is based on IGBT transistors with antiparallel diodes in the bridge configuration form the topology of the four-quadrant converter (Fig. 5). The alternating connections are M and N which connect of the transformer secondary, modelled using an alternating generator and a series-connected inductor L. The DC connections at the output of the converter are marked with P and Q. If we set the voltage-current coordinate system, the converter can work in two rectifier modes corresponding to the first and third quadrant and two inverter modes corresponding to the second and fourth quadrant. From this, we conclude that the converter has the possibility of two-direction power flow, one direction corresponds to the traction mode and the other corresponds to the recuperative braking mode, with the return of energy to the network. The inductance in series connection with the alternating voltage generator is modelled by the secondary of the traction transformer. The capacitor on the DC side has the role of damping the voltage pulsations by providing a constant voltage at the input connections of the voltage inverter for supplying the traction motors.

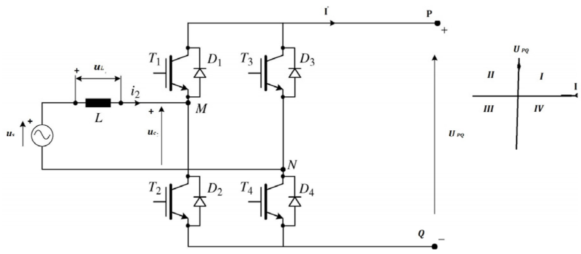


*Fig. 5. Scheme of the four-quadrant converter*

An important and first task that the converter has to fulfill is that the fundamental component of the current that the vehicle takes from the catenary has a power factor cosφ = 1. The second refers to the optimization of the alternating current distortion factor which measures the distortion in relation to the sinusoidal current. This goal is met by pulse width modulation, i.e. by conveniently varying the on time of static switches in the bridge branches forming a current close to the sinusoid (Fig. 6).

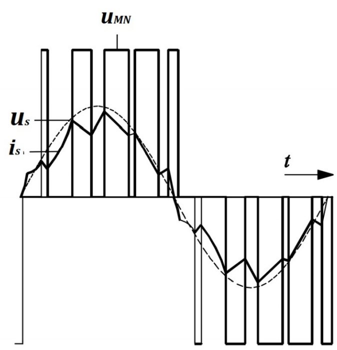


*Fig. 6. Current waveform from the AC power network, obtained by PWM in four-quadrant converter*

Comparative rewiev of the functional relation given with (6) for the analyzed locomotive types is given in the Fig. 7.

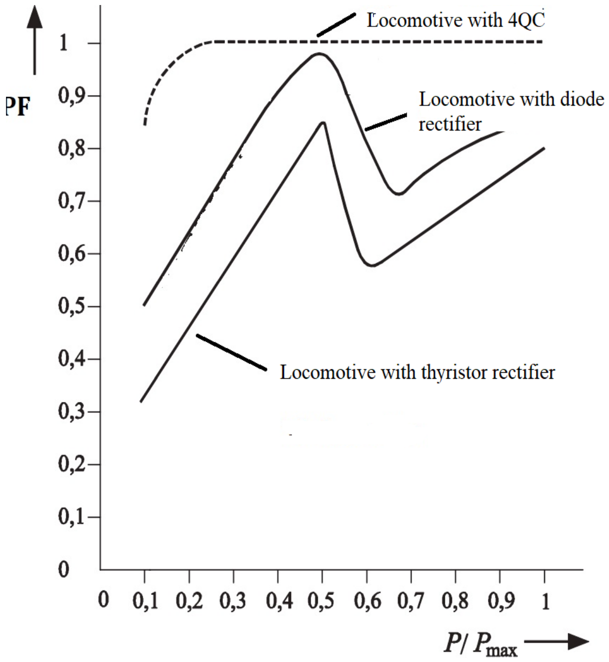


*Fig. 7. Dependence of the power factor of the analyzed locomotive types on the relative active power*

## 3. CONCLUSION

It is shown that various types of traction vehicles have a significantly different impacts on RMS current and distortion factor. Based on the presented comparative analysis, the conclusion is that a part of the transport cost on the electrified railway lines may be tied to a power quality coefficient, taking account the maximal power factor as a criterion.

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