

Measurement of distortion power and power factor in electric traction substations “Serbia railway infrastructure” when powering electric locomotives in traction and recuperative braking

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ABSTRACT

The aim of this paper is to point out the need to adapt the existing power measurement methods in electric traction substations of the "Railway Infrastructure of Serbia" in accordance with the provisions of the European standards EN 50470–1 and EN 50470-3:2022. The widespread use of power converters on electric locomotives, as typical non-linear consumers, has called into question the validity of existing methods of recording railway consumption. The waveform of the traction and regenerative braking current of electric locomotives deviates from the sinusoidal waveform, due to which part of the delivered energy remains invisible, which, among other things, leads to significant losses.

To solve this problem, it is necessary to detect and quantify the power factor that takes into account the power distortion due to the power supply of electric locomotives as nonlinear consumers. This manuscript proposes and describes indirect methods of measuring electricity with single-phase intelligent electricity meters that enable not only an efficient tariff policy, but also the need for compensation of higher harmonics at the point of connection of electric traction substations to the three-phase electrical network.

KEYWORDS

Voltage and current harmonics, Traction mode, Regenerative braking.

1. INTRODUCTION

The presence of higher current harmonics in the traction system of the "Serbian Railway Infrastructure" has a very negative impact on the elements of the transmission power system. This is because these elements are designed for optimal operation at a fundamental frequency of 50Hz, higher harmonics cause additional dissipation, significantly reduce their service life and lead to numerous other problems [1, 2, 3]. A large number of studies indicate that a true insight into the power delivered from the three-phase electrical network to the electric traction system of Serbian railways cannot be obtained by measuring only active and reactive power [4]. The nonlinear character of the consumers and the accompanying harmonic distortions of currents and voltages in the electric traction system, among other problems, have generated additional losses in the transmission network to the electric locomotives. Because of these losses, it is necessary to devise a reliable and at the same time economically justified method for registering the value of harmonic distortions.

Nonlinear harmonic distortions of current and voltage cause the appearance of a new power component that is not registered by the existing meters in traction substations. Namely, in addition to the active (P) and reactive power components (Q) that are measured, the distortion power (D_B) is not measured in traction substations. By measuring the distortion power (D_B) or by measuring the apparent power (S) and power factor both in the traction mode and in the recuperative braking mode of the trains, the presence of higher voltage and current harmonics at the point of connection of electric traction substations to the three-phase power grid is taken into account. In this way, the level of negative impact of the electric traction system as a pronounced nonlinear load on the three-phase power system can be measured in real time, all with the aim of taking appropriate protective measures.

In the following, we will describe the method measuring of: effective value of two-channel current and single-phase voltage, active power and power factor in accordance with the provisions of the European standards EN 50470–1 and EN

50470-3:2022, which are suitable for traction and regenerative braking of trains on electrified lines of the "Railway Infrastructure of Serbia".

2. APPARENT POWER COMPONENTS IN ELECTRIC TRACTION SUBSTATIONS FOR NONLINEAR LOAD CASE

According to the established tariff policy, "Railway Infrastructure of Serbia" only pays for active/reactive energy used. Installed electric meters in electric traction substations are not able to measure the energy that would eventually be accepted during recuperative braking of trains and transferred to the three-phase electrical network. Due to this fact, trains with the possibility of recuperating electricity still do not use this possibility, which reduces their energy efficiency.

The appearance of electric traction vehicles with recuperative braking requires the installation of various power converters based on semiconductors (diodes, thyristors, transistors). This fact created additional problems for the portable power grids that supply the single-phase electric traction system and electric locomotives with the possibility of recuperative braking. Part of the power that occurs due to the presence of higher harmonics, which is delivered or received by electric locomotives, is invisible from the point of view of the transmission power network if standard electro-mechanical or electronic meters are used for consumption registration. In the mentioned conditions, due to the presence of higher harmonics, the following relationship applies:

$$S^2 > P^2 + Q^2 \quad (1)$$

where: S - apparent power, P - active power, Q - reactive power.

Given that the following applies to simple periodic systems: $S^2 = P^2 + Q^2$, it is clear that the difference in the value of the apparent power originates from the presence of higher harmonics, that is, it is a consequence of voltage and current distortion in the electric traction system. Due to the presence of higher harmonics in the electric traction system, the distortion power must also be introduced so that the following corrected expression for the apparent power is valid:

$$S^2 = P^2 + Q^2 + D_B^2 \quad (2)$$

where D_B is the distortion power. The essence of this equation is that in the absence of harmonics $D_B=0$, $S^2 = P^2 + Q^2$ holds. It is obvious that this equality becomes a special case of applying equation (2). From equation (2) it follows that the distortion power is:

$$D_B = \sqrt{S^2 - P^2 - Q^2} \quad (3)$$

The addition of the D_B vector representing the harmonic distortion, as shown in Figure 1, creates a new power triangle for a true power factor with harmonics.

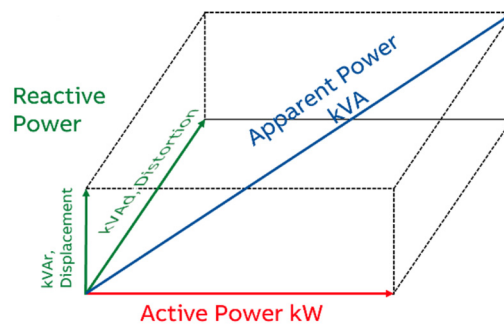


Figure 1: Power triangle for a power factor which includes harmonics

kW - Active Power is the power that performs useful work.

kVA - Apparent Power. Vectorial summation of kVAR and kW.

kVAR_R - Reactive Power.

kVAd - Reactive Power Distortion.

The power factor ($\cos \varphi$) under non-linear load conditions is:

$$P_F = \frac{P}{S} = \frac{P}{\sqrt{S^2 - Q^2 - D_B^2}} \quad (4)$$

Under linear load conditions ($D_B=0$), the power factor is:

$$P_F = \cos \varphi = \frac{P}{S} = \frac{P}{\sqrt{S^2 - Q^2}} \quad (5)$$

where is φ - the angle between the active and apparent power vectors.

Power factor and harmonics are two important concepts in electrical engineering, often discussed in the context of power quality and efficiency in electrical systems. Power factor defined in this way accounts for the harmonics thus reducing the total harmonic content contributing to the efficiency of the electrical system.

By measuring the power factor based on expression (4) and taking it into consideration when creating the account (penalization of significant non-linear consumers such as the electric traction system of the "Infrastructure of the Railways of Serbia"), the transmission power network as a distributor of electricity is able to significantly reduce the level of losses in the system and to reduce other problems that can cause the propagation of harmonics in the transmission network.

3. METHODS OF MEASUREMENT OF APPARENT POWER COMPONENTS IN ELECTRIC TRACTION SUBSTATIONS

The existing measuring equipment in electric traction substations provides a display of the consumption of active and reactive power/energy from the power grid, and when powering electric locomotives in the traction mode, i.e.:

Existing measuring equipment in electric traction substations allows the display of active and reactive power/energy from the power grid when powering electric locomotives in traction mode, i.e.: +P(kW), +W (kWh), +Q(kVAr), W_r(kVArh). However, with existing meters, measurement of active and reactive power/energy in electric traction substations (-P(kW), -W (kWh), -Q(kVAr), -W_r(kVArh)) is not possible due to the derived solution during regenerative braking of electric locomotives.

For the above reasons, the "Serbia Railway Infrastructure" must require new measuring equipment and methods, as well as improving the metrological characteristics of existing measuring equipment. This measuring equipment, in addition to being able to display the direction of electrical energy flow, must also provide reliable measurement of power factor under nonlinear load conditions of the electric traction system, which will indicate the efficiency of energy use and equipment performance. This includes assessing energy consumption patterns and identifying power factors under nonlinear load conditions of the electric traction system. The following text describes intelligent power factor measurement under nonlinear load in electric traction substations of the "Infrastructure of Serbian Railways" when powering electric locomotives in traction and regenerative braking modes.

3.1. Hardware Implementation of the Measurement Sistem

Regardless of the large number of electronic meters on the market today, the measurement data and software that are characteristic of these meters still do not allow the measurement of distortion power and power factor in conditions of two-way flow of electricity. Due to the stated reason, it can be said that only the described methodology and power factor measurement enables the necessary measurement in the "Serbian Railway Infrastructure". In addition, measuring the power factor P_F in electric traction substations in the mode of electric traction and recuperative braking of locomotives can directly indicate the efficiency of the use of electrical energy and the optimization of the performance of equipment in the electric traction system.

The hardware implementation of the proposed measuring system is shown in Figure 2. The measuring system is actually an adapted version of the existing electronic meters currently on the market. In this particular case, an electronic meter of single-phase electronic type EWGE11X (product of EWG from Niš, R. Serbia, www.ewg.co.rs) was used. This meter corresponds to European standards EN 50470-1 and EN 50470-3, as well as international standards IEC 62052-11, IEC 62053-21 and IEC62053-23.

EMG11X meter microcontrollers integrate:

- Analog inputs (analogue front end - AFE)
- Independent digital metrology unit (computation engine - CE)
- 8051-compatible microprocessor (MPU)
- LCD drivers
- RAM and Flash memory
- Real time clock (RTC)
- Greater number of multifunctional I/O pins.

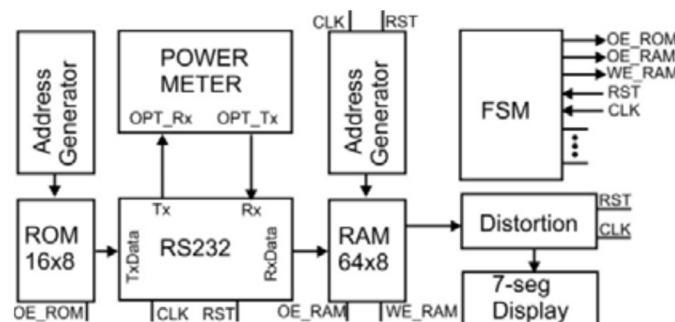


Figure 2: Block diagram of realized system

Figure 3 shows a block diagram of the two main microcontrollers used to implement the EWGE11X electronic meter.

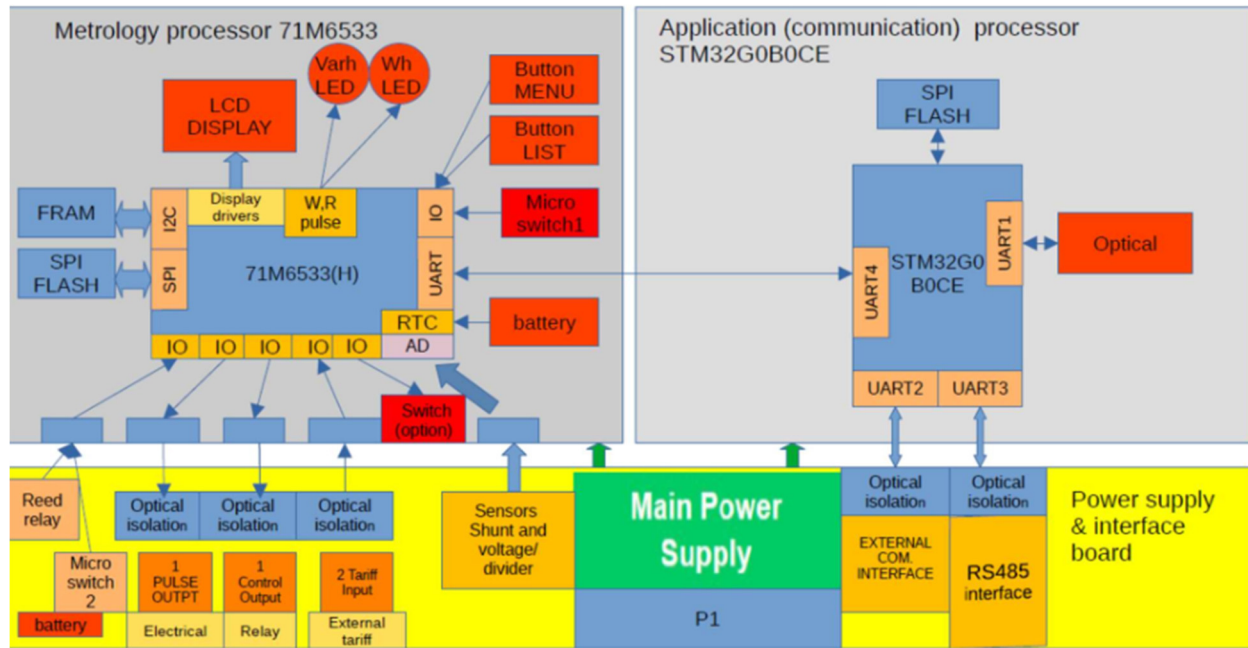


Figure 3: Microcontrollers of the electronic meter EMG11X - block diagram

The analog input functions as a data acquisition system controlled by a microprocessor unit (MPU). The basic blocks of the analog input are: input multiplexer, delta-sigma A/D converter, FIR filter and reference voltage block. Input analog signals are multiplexed before sampling using an A/D converter. The samples from the A/D converter are passed through the FIR filter and the filtering results are stored in the XRAM memory in the chip itself, where they can be accessed by the metrology unit (CE) or the microprocessor (MPU).

The metrological unit (CE) is a dedicated signal processor that performs the following metrological calculations:

- Multiplication of the instantaneous current value by the instantaneous voltage value to obtain the energy per sample, when multiplied by a constant sampling time.
- Gain and offset compensation.
- Sampling delay compensation on all channels (due to multiplexing of analog signals).
- 90° phase shift for reactive power Q calculation.
- Frequency measurement.
- Summation and calculation of effective values (RMS) of voltage and current.
- Calculation of fundamental and harmonics of active, reactive and apparent power.
- Calculation of fundamental and harmonics of current and voltage.
- Input signal frequency tracking (frequency and phase shift)
- Input signal amplitude tracking (delay detection)
- Temperature measurement and compensation.

Block diagram of the proposed meter for calculating the power factor under nonlinear load is shown in Figure 4. Namely, after multiplication, the AccSb block sums the squares of the active (P), reactive (Q) and distortion powers (D_B), and the square root of their sum is divided by the active power (P) (equation 4).

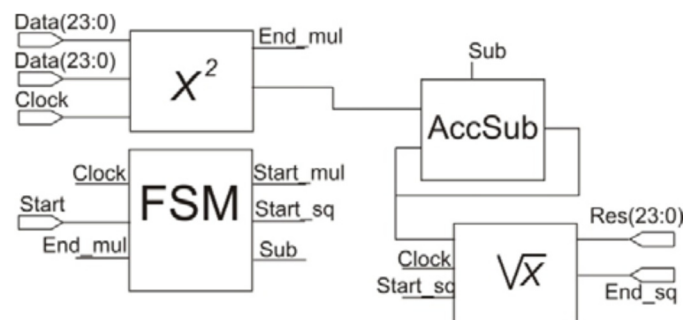


Figure 4: Block diagram for calculating the power factor under nonlinear load

The proposed meter is capable of recording all measured data in real time and transmitting it to a central location for billing purposes. In addition to providing accurate billing information, these meters can provide a number of other benefits. Namely, given the possibility of measuring the distortion power D_B and the power factor P_F , which takes this power into account, it is possible to measure the delivered power/energy, which has not been possible in electric traction substations so far, both in electric traction mode and during regenerative braking of electric locomotives. The described power meters were verified in the LEDA laboratory of the Faculty of Electronics, University of Niš, Republic of Serbia [20].

4. TARIFF SYSTEM

The described and proposed single-phase meter, which could be used in the "Railway Infrastructure of Serbia", allows for reliable determination of the level of vulnerability of the electric traction system with existing electric locomotives, as well as the three-phase power grid to which the 110/25kV electric traction substations are connected.

"Serbia Railway Infrastructure" has an interest in having electricity consumption in electric traction substations controlled by meters that register distortion power and power factor. Namely, the current practice is that the distributor covers losses by increasing the price of energy. In this way, losses caused by increased power/energy distortion are paid by all users, regardless of the nature of the consumers they use. Users who cannot afford expensive, energy-efficient devices will have increased bills as they cover the losses caused by energy-efficient devices! Also, those more conscious users who are willing to buy efficient devices with expensive filters to remove nonlinear distortions will also pay the costs of unscrupulous consumers. Therefore, there is a mutual interest (of distributors and consumers) to implement electronic meters that register both the energy consumption of the distortion and the power factor of that distortion.

In order to complete the system for registering electricity consumption burdened by nonlinear consumers, it is necessary to improve the tariff system. It is fair to discourage consumers from introducing harmonics into the electricity grid in an uncontrolled manner. For this reason, there is growing support for the need to introduce some allowable limit value for distortion power D_B , or power factor P_F , which would not be taken into account when creating the final bill for consumed electricity. At the same time, this means that the measured value of the distortion power D_B , i.e. the power factor P_F , should be reduced by that amount. We propose a correction that can be expressed using the form:

$$D_p = D_B - \gamma S \quad (6)$$

where D_B and γS represent the value of the measured distortion power and apparent power, respectively, and γ denotes a constant to be defined. The decision on the value of the constant γ that will correct the measured values would be made by railway experts in agreement with electricity distributors. The authors of this manuscript propose that the value of the coefficient γ be 0.1. The aforementioned value was obtained after considering the permissible value of voltage/current harmonics at the connection point prescribed by the IEEE 519-2022 standard. This standard was considered a reference, instead of IEC61000-3-2:2019, which is mainly applied in Europe, for a very pragmatic reason. Namely, IEC61000-3-2:2019 regulates the characteristics of electronic devices, while the IEEE 519-2022 standard defines the permissible values of voltage/current harmonics at the point where the consumer is connected to the three-phase electrical network, i.e. at the point of connection of the electronic meter. It is important to note that these standards are compatible, so compliance with the IEC61000-3-2:2019 standard also guarantees compliance with the requirements prescribed by the IEEE 519-2022 standard.

5. CONCLUSION

The presence of higher current harmonics in the traction system of the "Railway Infrastructure of Serbia" has an extremely unfavorable effect on the elements of the three-phase electrical system. Since they are typically designed to operate optimally at a fundamental frequency of 50Hz, higher harmonics cause additional dissipation, significantly shorten equipment life, and lead to numerous other problems.

Modern electric traction drives are designed in accordance with the requirements of increasing energy efficiency, and therefore very often a part of the energy from electric locomotives can be returned to the three-phase power grid via contact network and electric traction substations. Apart from the economic aspect of reducing consumption, electric locomotives with regenerative braking introduce non-linear effects associated with the injection of currents that are extremely rich in higher harmonics. That is why it is important to quantify the non-linear component that is introduced into the power grid via electric traction substations.

Due to all of the above, the research results indicate the need to change the electricity charging policy, i.e. the need to compensate for higher harmonics at the connection point of traction substations of the Serbian Railway Infrastructure. This intervention is not cheap, and its optimal implementation requires serious techno-economic analysis. Due to all of the above, it is proposed to bill electricity using electronic meters with the described measurement method, which allow, under conditions of highly nonlinear load, precise measurement of various electrical quantities, including positive and negative distortion power and power factor, which have not been measured in traction substations so far.

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