Reactive power compensation in the railway electrical traction system, using synchronous machines controlled by SCADA

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Abstract. This article brings forward a solution for compensating the reactive power of the railway electrical traction system. Using the V-characteristics of the synchronous machine, reactive power can be produced or absorbed from the power supply network, keeping the power factor at a value as close to 1 as possible. Given that the load consumed by the railway electrical traction system is variable, it is necessary to be able to promptly correct the power factor. The SCADA system will change the synchronous machine’s operating characteristics relative as a function of the angle between the voltage and the current that are set at a given time by the consumers (electrical locomotives) passing through the railway section. By compensating the reactive power, the amount of active power supplied to the electrical network of the railway traction system is increased, without the need to modify the cross-section of the electrical conductors.

1. Introduction
The electrical railway transportation system (ERTS) employs electrical locomotives and railcars, with a 1-hour peak power between 600 and 6600 kW. In addition to the absorption of active power from the network, the functioning of the rolling stock requires absorption of reactive power. This leads to a drop in the system’s power factor.

Continuous operation of the ERTS with the power factor under the neutral value (the agreed-upon limit above which expended reactive power is not billed) negatively impacts the cost price of railway transport. It has been shown that the lack of power factor compensation has led to the rise of cost price of consumed and billed electricity by approximately 110% over 30 days, over roughly 60 km of railway [1].

Power factor compensation at power supply points of the ERTS increases the available active power that can at one time be delivered to the traction system. Additionally, electrical overloads are eliminated from the power system, which in turn increases the stability of the supply and distribution of electrical power [2].
2. Methods used for power factor compensation

2.1. The need to compensate the power factor in the ERTS

Table 1 consists of data recorded for a period of 30 days at an electric traction substation (ETS). The interpretation of the data in the table shows that the ERTS consumed, per ETS, for a period of approximately one month, as follows: invoiced active energy was 549071.04 kWh (Wa) and invoiced reactive energy was 2148073.15 kVArh (Wr). Using the billing calculation methodology applied at this moment (according to ANRE - National Authority for Reglementation of Energy - Order no. 33 of May 28 2014) for the active and the reactive energy, the following values were obtained:

- invoiced active energy was 113404.58 RON
- invoiced reactive energy was 123739.72 RON

Table 1. Energy cost for July 2017 (MPS).

| State   | Date       | Wa [kWh] | Wr [kVArh] | Cost Wa [RON] | Cost Wr [RON] |
|---------|------------|----------|------------|---------------|---------------|
| Normal day | 02.07.17 24h | 134310.3 | 9680       | 94294.79      | 0.00          | 2770.82       | 6931.42       |
| Max. Wa | 08.07.17 24h | 176644.26 | 0          | 73004.56      | 34858.11      | 3644.17       | 4102.86       |
| Max. Wr | 25.07.17 24h | 146188.08 | 0          | 65647.47      | 77564.02      | 3015.86       | 3689.39       |
| Month   | 31.07.17 744h | 5497071.04 | 26850.60   | 2121222.55    | 1138097.76    | 113404.58     | 123739.72     |

Total energy invoiced for the analyzed period amounted to 237144.3 RON. An interesting point to consider is that for 549071.04 kWh, a doubling of the cost price for each kWh of consumed active energy is observed, caused by the lack of compensation of reactive energy.

The average power factor achieved for the invoiced interval is determined based on active energy consumed from the network and the reactive energy transited through the invoiced point, using the following formula:

\[
cos\phi = \frac{W_a}{W_{ap}},
\]

where \( W_{ap} = \sqrt{W_a^2 + W_r^2} \).

Taking the above into consideration, the resulted average power factor for the billing interval (\(cos\phi\)) is 0.85. Clearly, this value shows that the ERTS has an inductive operating regime that must be corrected by compensating the reactive power in each electric traction substation.

Given that the ERTS operates on single phase current, supplied at \(UN = 25\) kV from 16 MVA transformers in electrical traction substations (ETSs), the power factor compensation is accomplished by using single-phase compensators dimensioned to the maximum value of the apparent power provided by the power source [3].
2.2. Static compensation using capacitor banks

The static method of power factor compensation in the ERTS, using capacitor banks, requires connecting the capacitor bank with the power source and the load, in parallel [4, 5]. The reactive power provided by the capacitor bank can be dimensioned for either total compensation, or partial compensation.

The following mathematical statements hold true:

Reactive power absorbed by the ERTS is:

\[ Q = U \times I \times \sin \varphi, \]  \hspace{1cm} (2)

and the reactive power provided by the capacitor bank is:

\[ Q_c = U \times I_c = \omega C U_f^2, \]  \hspace{1cm} (3)

From the equality of the two powers:

\[ C = \frac{I \times \sin \varphi}{\omega U_f^2}, \]  \hspace{1cm} (4)

For partial power factor compensation:

\[ C = \frac{\Delta Q}{\omega U_f^2}, \]  \hspace{1cm} (5)

where: \( \Delta Q = Q_1 - Q_2 \), \( Q_1 \) = total reactive power consumed by the ERTS, and \( Q_1 \) = total reactive power consumed at a power factor \( \cos \varphi < 0.9 \).

Given that current regulations pertaining to the consumption and billing of electrical energy do not require total compensation of the power factor, it is sufficient to perform partial compensation, up to the neutral factor of \( \cos \varphi = 0.9 \).

Through the introduction of capacitive current in the system, the inductive current demanded by the asynchronous motors of the ERTS is compensated. This method of compensation has the following drawbacks:

- the adjustment of compensation can only be done in steps, there is no possibility of continuous adjustment;
- providing additional insulation for the capacitor banks used at medium voltage entails additional costs and certain limitations;
- increased risk of loading the system with reactive capacitive electrical energy, which leads to loading the system as in the case of not compensating inductive reactive energy.

2.3. Compensation using synchronous machines

The synchronous machine (SM) is a piece of electrical equipment that can function as a generator, motor or as a synchronous compensator that produces reactive energy. The operation mode of a SM can be changed by modifying the \( \Theta \) angle between the electromotive voltage induced in the stator winding and the voltage measured at the winding’s posts. The \( \Theta \) angle can take values between 0 degrees when idling and \( \pm 90 \) degrees for maximum load in the generator or motor modes.

Synchronous compensators (SC) are idling synchronous motors, built for the purpose of providing reactive power. They are similar to capacitor banks, but with the added advantage of allowing for continuous adjustment of the reactive power.

The reactive power of a SC can be determined using this equation:

\[ Q = m \times U \times I_a \times \sin \varphi \]  \hspace{1cm} (6)

where \( m \) is the number of phases of the SC.

The synchronous reactive power compensator can introduce power to the system, or absorb power from it, according to the excitation current applied to the excitation winding. The “V” characteristics
of the SC show the functioning regimen of the machine in relation to the variation of the excitation current (figure 1).

![Figure 1. 'V' characteristics of the synchronous compensator.](image)

By modifying the excitation current, the SC can be set to one of three different states:
- overexcited – the \( I_a \) current is capacitive – the SC provides reactive power;
- optimal – the \( I_a \) current is resistive – the SC doesn’t absorb or provide reactive power;
- underexcited – the \( I_a \) current is inductive – the SC absorbs reactive power.

The characteristics of SC adjustment show the relationship between the load current \( I \) and the excitation current \( I_e \) when the SC functions in parallel with the power source of the ERTS.

2.4. Adjustment of the excitation current of the SC

There are two stages in the control of the excitation current.

The theoretical stage:
- First, the nominal excitation current is determined from the \( V \) characteristic and the \( \cos \phi = f (I_a) \) characteristic of the SC, both increased to nominal operation values;
- The excitation current is determined. This current is necessary to compensate the longitudinal and transversal reaction effect of the rotor;
- The adjustment coefficients of the excitation currents are defined, depending on the current power factor and the one that is desired.

The practical stage:
- The measurement block collects the values of voltage, current, reactive and active power;
- Using the SCADA system controlling software, the collected values are analyzed. The excitation current generator is given a command, proportional to the difference between the existing power factor and the target power factor;
- The result is the modification of excitation current, increasing or decreasing the reactive power in the system.

Figure 2 shows a block diagram of the automation of the excitation current control, introduced in the SCADA system.
Figure 2. Diagram of SC excitation current control. BMC = common measurement block; AP = programmable logic controller; SC = supervision and control unit; GE = excitation current generator.

2.5. Advantages to the use of SC
Reactive power compensation using SCs in the ERTS has the following advantages:
- the SC allows for the continuous adjustment of reactive power provided to or absorbed from the ERTS;
- SC can be produced with a specification of $Q_{\text{max}} = 200 \text{ MVArh}$, thus avoiding the limitations of using capacitor banks;
- the risk of introducing capacitive reactive energy in the ERTS through compensating inductive reactive energy is avoided.

3. Compensation of reactive power in ETSs
Electrical traction substations provide power to the ERTS using 16 MVA transformers. Typically, one transformer is functioning and the other one is kept as a backup. The functioning of ETSs at a power factor of $\cos \phi > 0.9$ necessitates the compensation of reactive power consumed by the ERTS. This is accomplished through parallel-coupling to the STE transformer of a SC dimensioned for the apparent power provided by said transformer.

Compensating the reactive power absorbed by the ERTS permits keeping one transformer as a backup, given that it results in increased active power availability from the functioning transformer, up to the value of installed active power [6].

4. Control of the SCs utilizing the SCADA (Supervisory Control and Data Acquisition) system
The SCADA system consists of a main server and multiple Programmable Logic Controllers (PLC) and/or Remote Terminal Unit (RTU) with the purpose of monitoring and controlling the connected equipment at ETS level. The network schematic is presented in figure 4.

A PLC or RTU collects the $U$, $I$, $\phi$, and $\cos \phi$ and $I_c$ values from the measurement cell of the running transformer. It then transmits the values to a microcontroller for analysis, and to a display for visual control [7].

If the microcontroller reads a $\cos \phi < 0.9$ it will analyze the $\phi_0$ angle between $U$ and $I$. If $\phi_0 > 0$ then the load is said to be inductive ($X_L > X_C$) and the microcontroller will increase the value of the excitation current $I_{ex}$, and will overexcite CS for the introduction of reactive energy in the system.

Conversely, a $\phi_0 < 0$ means the load is capacitive ($X_C > X_L$) and the microcontroller will decrease the excitation current $I_{ex}$, and will underexcite the SC which will absorb reactive energy from the system.
Figure 3. Single-wire schematic of an ETS containing an SC, parallel-coupled with the power transformers. EL-electrical line; ETS-electric traction substation; TR1, TR2-transformer 1,2; SC-synchronous compensator; F1, F2-Feeder 1,2; RF- Return feeders; EL-Electrical locomotive.

Figure 4. Schematic illustrating the use of SCADA in monitoring and controlling ETS equipment.
If \( \cos \varphi \geq 0.9 \) and \( \varphi_0 = 0 \) (\( XL = XC \)) the circuit is resistive; the microcontroller will repeatedly attempt to read the parameters.

The principle of functioning of SCADA-assisted control of the SC is shown in figure 5 [7, 8].

The implementation of power factor control and SC control in the SCADA system which controls the ETSs is done in the Citect SCADA software. After programming and restarting the SCADA system, the operator can control the system, and the HMI (Human Machine Interface) software will display the real-time variation of the parameters on an LCD monitor (see figure 6) [8, 9].

5. Conclusions

Prior to power factor compensation, the ETS had a monthly electricity bill of 237144,3 RON ($55152 at the current exchange rate), of which only 113404,58 RON ($26374) represent consumed active energy.

Following the introduction of SCADA-controlled power factor compensation, the total billed value of electrical energy decreased by approximately 51% [10].

Power factor compensation decreased the load of the running transformer of the ETS. Load peaks that previously occurred at certain hourly intervals have been eliminated. Additionally, it allowed for keeping the second transformer as a backup, the power reserve of active power at the ETS has been increased, and implicitly the power supply system’s stability has been improved.

Using SCADA-controlled SCs for power factor compensation permits the real-time continuous adjustment of the parameters of the electrical energy supplied to the ERTS.

Increased power flow is ensured for the involved segment of the installation, as well as the uniformity of voltage for the entire area supplied by the ETS in question. This has resulted in the supplied electricity parameters being adequate for the rolling stock of the ERTS.

The reduction of electrical energy cost for electric railway transport is a problem that concerns both the electrical energy providers and the railway traffic operators. Making the ERTS profitable through the reduction of energy cost results in the continued development and modernization of the transport system, a goal pursued by all market players.

![Figure 5. Logic flowchart of SCADA power factor control.](image-url)
Figure 6. Single-wire schematic of an ETS introduced in the SCADA system.

References

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