Reactive power sources control in railroad power supply systems

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Abstract. This article presents computer modeling results for AC railroads power supply system modes. It considers various methods of connection of controlled reactive power sources (RPS). It is shown that the various problems of stabilizing the voltage levels in the traction network and reducing electrical energy losses can be solved. The computer-aided modeling indicates that to install RPS into all phases of traction substations is the best way to stabilize voltage levels in traction networks and reduce electrical energy losses. When the reactive power sources are present in the free phase, traction network losses increase in comparison with the option when the RPS are not present. The installation of sources in the retarding or leading phase allows stabilizing voltage in the load utilizing equipment, reducing losses and non-symmetry in supply mains. The best option in terms of electrical energy losses is connecting the RPS to the leading phase. In terms of non-symmetry in supply mains, the best performance is produced when the RPS are installed in the retarding phase.

1. Introduction.
Some problems related to low power quality and low energy efficiency [1 – 6] occur in AC railroads traction power supply systems (TPSS). These problems can be resolved using smart grids technologies with comprehensive facilities to control modes [7, 8].

These facilities include reactive power sources (RPS), the application of which in TPSS is discussed in works [9 – 16]. Results obtained in these works serve as a methodological basis to carry out further research aimed at the implementation of technologies of the effective use of controlled RPS in traction power supply systems.

Smart grid technology introduction is impossible without the development of the tools of modeling of TPSS modes equipped with active devices for controlling modes [2, 8]. The Fazonord software system designed in Irkutsk State Transport University can be used effectively as such a tool [3]. This article provides the results of modeling of TPSS modes based on this software with respect to the rational placement of adjustable RPS in traction networks.

2. Problem formulation.
Reactive power sources can be placed at different points of the traction network [16, 17]. Below are the modeling results and the comparative analysis of the TPSS efficiency, which use the following options of RPS installation (Fig. 1):

1. without the RPS installation;
2. RPS at all terminals of the 27.5 kV traction substation (TS);
3. RPS in the retarding phase (BC);
4. RPS in the leading phase (AC);
5. RPS in the free phase (AB).

Reactive power generation and consumption limits were set from \(-5\) to \(5\) Mvar for each RPS installation option.

Controlled sources of reactive power can be used to solve the following problems:
1. the stabilization of traction network (TN) voltage levels.
2. the reduction in electrical energy losses in TPSS and the external power supply system;
3. the reduction of non-symmetry at high voltage buses of traction substations;

The first problem is the most important for transport. Its formalized record can be represented in the following way:

\[
\sum_{j=1}^{n} \sum_{k=1}^{m} (U_j(t_k) - U^Z_j)^2 \rightarrow \min ;
\]  

while having limitations

\[
F(X(t_k), Y(t_k)) = 0;
\]

\[
Q_{j}^{(\min)} \leq Q_{j} \leq Q_{j}^{(\max)},
\]

where \(U_j(t_k)\) is the voltage on load utilizing equipment of the \(j\)th train in time moment \(t_k\), kV; \(U^Z_j\) is the voltage level set at the load utilizing equipment of the \(j\)th train, kV; \(F\) is the non-linear vector-function, corresponding to equations describing the \(k\)th mode of the TPSS instant scheme; \(X(t_k)=[x_1(t_k), x_2(t_k), \ldots, x_j(t_k)]^T\) is the uncontrolled parameters’ vector for the \(k\)th mode of the TPSS instant scheme; \(Y(t_k)=[y_1(t_k), y_2(t_k), \ldots, y_j(t_k)]^T\) are uncontrolled parameters vector for the \(k\)th mode of the TPSS instant scheme; \(Q_{j}^{(\min)}, Q_{j}^{(\max)}\) are RPS reactive power change limits.

**Figure 1.** RPS arrangement schemes by phases: a – RPS at supply branches; b – RPS at TS terminals

Modeling of TPSS modes where TPSS are equipped with RPS with objective function (1) can be performed based on the Fazonord software application [3]. For this purpose, swing-buses are set at RPS terminal points in terms of reactive power which correspond to the following equations [2, 3]:

\[
(U_k)^2 + (U_k)^2 - (U^Z_k)^2 = 0; \quad Q_{k}^{(\min)} \leq Q_{k} \leq Q_{k}^{(\max)}.
\]
3. Modeling results.

The design model scheme corresponding to Fig. 1 is shown in Fig. 2. Maintaining voltage level of 27.5 kV at its terminal point is accepted as the aim of reactive power sources’ control. During the modeling, the operation of five trains weighing 6,000 tonnes each was considered in even direction, and the same number of trains each weighing 3,200 tons were considered as moving in odd direction. The train schedule is shown in Fig. 3. The current profiles of the trains are shown in Figs. 4 and 5.

RPS installation options were compared by the following parameters:

- voltage levels under the train load utilizing equipment (Table 1, Fig. 6);
- non-symmetry coefficients for negative sequence at the high-voltage buses of the traction substations (Fig. 2, Fig. 7);
- losses in active energy in TPSS and the external power supply system (Table 3);
- powers generated (consumed) by RPS (Table 4).

![Figure 2. RPS at TS medium voltage buses: OPL is the overhead power line; ISZ is the inter-substation zone; OS are the overhead system sections](image)

![Figure 3. Train schedule](image)
Figure 4. Even train current profile

Figure 5. Odd train current profile

Table 1. Voltage levels under the train load utilizing equipment, kV

| Train number | 1         | 2         | 3         | 4         | 5         | 6         | 7         | 8         | 9         | 10        | For all trains |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|------------|---------------|
|              | without RPS installation |           |           |           |           |           |           |           |           |            |               |
| Min          | 22.87     | 22.87     | 22.84     | 22.84     | 23.02     | 21.87     | 20.50     | 20.50     | 20.91     | 22.06      | 20.5         |
| Mid          | 26.55     | 26.11     | 25.91     | 25.98     | 26.35     | 25.76     | 25.32     | 25.29     | 25.45     | 26.03      | 25.875       |
| Max          | 27.96     | 27.80     | 27.88     | 27.95     | 28.01     | 27.85     | 27.81     | 27.76     | 27.75     | 27.94      | 28.01        |
|              | RPS installation in all TS phases |           |           |           |           |           |           |           |           |            |               |
| Min          | 23.73     | 23.73     | 24.32     | 24.15     | 24.15     | 23.16     | 22.24     | 22.24     | 22.56     | 23.32      | 22.24        |
| Mid          | 26.89     | 26.66     | 26.52     | 26.48     | 26.68     | 26.24     | 25.98     | 25.97     | 26.10     | 26.43      | 26.395       |
| Max          | 27.71     | 27.64     | 27.69     | 27.74     | 27.68     | 27.63     | 27.60     | 27.60     | 27.53     | 27.60      | 27.74        |
|              | RPS installation in the retarding phase (BC, node 26) |           |           |           |           |           |           |           |           |            |               |
| Min          | 23.10     | 23.10     | 23.58     | 23.94     | 23.94     | 22.83     | 21.82     | 21.82     | 22.18     | 22.70      | 21.82        |
| Mid          | 26.75     | 26.50     | 26.39     | 26.46     | 26.67     | 26.15     | 25.81     | 25.79     | 25.90     | 26.30      | 26.281       |
| Max          | 27.92     | 27.82     | 28.05     | 28.16     | 28.25     | 27.89     | 27.96     | 28.04     | 28.04     | 28.23      | 28.25        |
|              | RPS installation in the leading phase (AC, node 21) |           |           |           |           |           |           |           |           |            |               |
| Min          | 23.64     | 23.64     | 22.88     | 22.88     | 23.03     | 21.93     | 20.62     | 20.62     | 20.99     | 21.97      | 20.62        |
| Mid          | 26.79     | 26.38     | 26.13     | 26.07     | 26.29     | 25.88     | 25.57     | 25.56     | 25.71     | 26.17      | 26.055       |
| Max          | 27.92     | 27.78     | 27.66     | 27.61     | 27.66     | 27.63     | 27.61     | 27.61     | 27.53     | 27.64      | 27.92        |
|              | RPS installation in the free phase (AB, node 40) |           |           |           |           |           |           |           |           |            |               |
| Min          | 22.71     | 22.71     | 22.51     | 22.51     | 22.74     | 21.32     | 20.11     | 20.11     | 20.52     | 21.68      | 20.11        |
| Mid          | 26.33     | 25.87     | 25.66     | 25.73     | 26.10     | 25.54     | 25.10     | 25.07     | 25.23     | 25.78      | 25.641       |
| Max          | 27.79     | 27.64     | 27.79     | 27.80     | 27.84     | 27.75     | 27.71     | 27.65     | 27.56     | 27.79      | 27.84        |
Analysis of Table 1 data allows making the following inferences:

– the highest voltage fluctuations difference under the electric locomotive load utilizing equipment is observed in the absence of RPS.

– the least voltage stabilization effect is observed when RPS are connected to AB linear voltage (in the free phase);

– the best stabilization effect is observed when three reactive power sources are installed (option 2 which is the most expensive).

![Figure 6](image)

**Figure 6.** The minimal, mid, and maximal voltage level under the load utilizing equipment subject to RPS installation option.

| Parameter | Traction substation | TS 1 | TS 2 | TS 3 |
|-----------|---------------------|------|------|------|
|           | without the RPS installation |      |      |      |
| Min       | 0.04                | 0.04 | 0.04 |      |
| Mid       | 1.04                | 1.38 | 1.52 |      |
| Max       | 2.52                | 3.78 | 4.41 |      |
|           | RPS installation in all phases |      |      |      |
| Min       | 0.05                | 0.06 | 0.08 |      |
| Mid       | 0.58                | 0.72 | 0.85 |      |
| Max       | 1.95                | 2.66 | 3.1  |      |
|           | RPS installation in the retarding phase (BC, node 26) |      |      |      |
| Min       | 0.26                | 0.29 | 0.32 |      |
| Mid       | 0.81                | 1.08 | 1.24 |      |
| Max       | 2.12                | 3.17 | 3.74 |      |
|           | RPS installation in the leading phase (AC, node 21) |      |      |      |
| Min       | 0.11                | 0.13 | 0.11 |      |
| Mid       | 0.99                | 1.38 | 1.58 |      |
| Max       | 2.51                | 3.79 | 4.45 |      |
|           | RPS installation in the free phase (AB, node 40) |      |      |      |
| Min       | 0.07                | 0.10 | 0.11 |      |
| Mid       | 0.98                | 1.43 | 1.67 |      |
| Max       | 2.59                | 3.92 | 4.57 |      |
Results provided in Table 2 and illustrated in Fig. 7 indicate that it is the most expensive option No. 2 that ensures the best effect in non-symmetry reduction at high voltage buses at the traction substations (maximum $k_{2u}$ is reduced to 3.1%). When RPS are installed in the retarding phase, $k_{2u}$ coefficient maximum is reduced to 3.7%. The growth in non-symmetry coefficient maximal value corresponds to option 4. A similar result is observed in option 5.

Table 3. Active energy losses in OPL, CT, OS, kW

| The mains element | The RPS installation option |
|-------------------|-----------------------------|
|                   | 1  | 2  | 3  | 4  | 5  |
| OPL-1             | 500.3 | 408.8 | 489.0 | 469.4 | 430.7 |
| OPL-2             | 122.4 | 90.2 | 125.2 | 101.6 | 143.7 |
| OPL-3             | 28.0  | 22.7  | 28.2  | 23.3  | 32.4  |
| **Amount**        | **650.7** | **521.7** | **642.4** | **594.3** | **606.8** |
| Transformer 1     | 263.6  | 254.8  | 258.1  | 260.3  | 260.5  |
| Transformer 2     | 281.6  | 258.8  | 276.2  | 267.1  | 309.8  |
| Transformer 3     | 249.4  | 243.8  | 250.1  | 244.8  | 251.5  |
| **Amount**        | **794.6** | **757.4** | **784.4** | **772.2** | **821.8** |
| OS-1              | 658.5  | 635.9  | 643.3  | 643.3  | 659.7  |
| OS-2              | 561.1  | 519.3  | 558.5  | 517.7  | 584.6  |
| **Amount**        | **1219.6** | **1155.2** | **1201.8** | **1161** | **1244.3** |
| **Total:**        | **2664.9** | **2434.3** | **2628.6** | **2527.5** | **2672.9** |

The second option is the best in terms of electrical energy losses; in this case the total losses are reduced approximately by 9%. The 4th option is characterized by a good performance yielding this index reduction by 5%. When RPS is installed in free phase, a little increase in losses occurs.

Reactive power generation (consumption) values are provided in Table 4.
Table 4. Summary data for RPS reactive power generation (consumption), Mvar

| Factor          | Option 2 | Option 3 | Option 4 | Option 5 |
|-----------------|----------|----------|----------|----------|
| Node number     | 21       | 26       | 21       | 21       |
| Min             | –5       | –2.71    | –3.44    | –3.44    | –2.71    | –5       |
| Max             | 5        | 5        | 5        | 5        | 5        | –2.48    |

Analysis of Table 4 data indicates that the broadest range for adjustment from –5 to +5 Mvar is required for option 2, whereas the least (from –2.7 to +5) is required for option 4.

Contemporary multiagent control systems [1, 8, 18] make it possible to set more complicated RPS control tasks. To these one can refer the problem of RPS optimal setpoints choice, where RPS ensures electrical energy losses minimizing in traction network along with voltage (1) levels stabilization:

$$dW = \sum_{k=1}^{s} \left( \int_{0}^{T} dP_k(t) dt \right) \rightarrow \min ,$$

(4)

where \(s\) is the number of TN elements considered; \(dP_k(t)\) are power losses in the \(k^{th}\) element of TN.

The formulated control task is reduced to the search of the RPS setpoint vector:

$$U_{2\text{rps}} = [U_{2\text{rps}}^1, U_{2\text{rps}}^2, ..., U_{2\text{rps}}^s]^T,$$

which ensures minimization of functionals (1) and (4) for each discrete time moment in case of limitations (2) and (3).

4. Conclusion

The modeling method of traction power supply systems modes proposed in this article, where traction power supply systems are equipped with adjustable reactive power sources, can be used to solve the following urgent practical issues:

– rational RPS arrangement in traction network;
– development of actions aimed at voltage levels stabilization under the electric locomotive load utilizing equipment;
– enhancing power quality in 110-220 kV mains supplying traction substations;
– raising energy efficiency of traction power supply systems.

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