Table 1. Final statistic of powers.

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<th>Day</th>
<th>$P_{max}$</th>
<th>$P_{peak}$</th>
<th>$P_{ave}$</th>
<th>$P_{var}$</th>
<th>$P_{min}$</th>
<th>$P_{ave}$</th>
<th>$P_{var}$</th>
<th>$P_{min}$</th>
<th>$P_{ave}$</th>
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<td>4.54</td>
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<td>2.41</td>
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<td>4.44</td>
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<td>3.53</td>
<td>2.65</td>
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<td>2.41</td>
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</tr>
<tr>
<td>24.2</td>
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<td>6.17</td>
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<td>26.1</td>
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<td>11.5</td>
<td>9.89</td>
<td>9.46</td>
<td>8.61</td>
<td>7.61</td>
<td>3.42</td>
<td>2.85</td>
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Table 2. Count coefficient.

<table>
<thead>
<tr>
<th>$C_1$</th>
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<td>27.2</td>
<td>3.99</td>
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3. CONCLUSION

Development of load is characterised by great irregularities and great ranges of values. Also from measured time developments of current and power one of the basic characteristics of electrical traction is clear and that is great dynamics. From the daily development we can observe power peaks representing traffic peaks.

From the development of load several important values were derived, which are deciding for dimensioning of traction transformer substations.

From the development of powers we can gather that the maximum of one minute, five minutes, fifteen minutes, one hour as well as two hours power are substantially lower than the maximum of the instantaneous.

REFERENCES


Fig. 1. Typical scheme of traction substation supplying system in Poland (SEE = power system; MW = medium voltage (typically 15 kV))

busses; L = supplying line; TS = traction substation)

The second important aspect, which must be taken into consideration, are voltage fluctuations $\Delta U_{AC}(t)$ at AC buses (flickers) caused by changing load $\Delta U_{AC}$ of electric traction substation, which may be described as voltage drops at power supply elements described by resistance $R$, reactance $X$ and power characteristic $\cos \phi$ divided by nominal voltage $U_{AC}$:

$$\Delta U_{AC}(t) = \sqrt{R^2 + X^2 \cos \phi^2} \cdot U_{AC}(t)$$

It is resulted from power demand profile of electric locomotives – starting and coasting ride. Rapid traction load variations can be observed as significant voltage variations. The lower are power supply short-circuit power, the higher are influence of electric traction.

These two above mentioned phenomena can cause an improper operation of loads sensitive to energy quality: flickering, bad working of computers, measuring devices, remote control devices, telecommunication devices, electric machines etc. For these reasons, it is very important to estimate above phenomena, both for designing and existing electric traction systems.

3. SIMULATION MODEL

In order to assess the influence of the electrified railway line model of electrified railway line oriented towards power balance has been used [3]. The input data are following:

- supply system parameters
- time – table of trains
- route characteristic (vertical gradient, curves, speed limits)
- rolling stock parameters.

Such model allows simulating the operation of electrified railway line in each second. The results of simulation are for example voltage and current courses.

After the simulation is finished, an analysis of voltage distortion and variations in selected nodes are performed.
supply system values and load parameters.

As an example of the application of the model, a part of being modernized railway line Warsaw – Lodz has been taken into account with two options of the traffic and power supply schemes:

- parameters of existing line (option 0),
- parameters of designed supply system for the forecasted traffic (option 2).

Those aspects have to be taken in particular consideration because of traction substation supply system configuration. In both options, some traction substations are supplied from neighboring traction’s AC busbars (B in Fig. 2).

Fig. 2. Traction substation supply system from AC busbars of a neighboring traction substation - (option 0).

Fig. 3. Traction substation supply system from AC busbars of a neighboring traction substation - (option 2) (D,E,F-new designed traction substations).

Basic parameters of the power supply system are shown in tables 1a + 1b.

Tab. 1a. Supply system parameters (option 0)

<table>
<thead>
<tr>
<th>TS</th>
<th>A&quot;</th>
<th>B&quot;</th>
<th>C&quot;</th>
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<tbody>
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<td>3 x PK17</td>
<td>3 x PK17</td>
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<tr>
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</tr>
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<tr>
<td>Sn</td>
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Tab. 1b. Supply system parameters (option 2)

<table>
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<tbody>
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<td>R</td>
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</tr>
<tr>
<td>Sn</td>
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<td>1500</td>
<td>1155</td>
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</table>

1) Type and number of rectifier groups [-]
2) Supply system (S = PCC; TS – AC busbars of a neighboring traction substation)
3) Rated power of transformer 110/15 kV [MVA]
4) Short-circuit power (PCC-HV busbars) [MVA] PK17-6-pulse; PD16-12-pulse

4. SIMULATION RESULTS

For option 0, simulation was performed assuming 3-hour peak period of traffic on the line. There are shown in Figures 4 + 7 results of simulations and analysis results obtained for the worst case - TS „C“ AC busbars, which additionally supply TS „B“ (results shown in Figures 8 + 11).

Fig. 4. Voltage Total Harmonic Distortion (THD) calculated at TS „C“ AC busbars (option 0)

Fig. 5. Voltage flickers calculated at TS „C“ AC busbars and compared to assumed criteria (option 0).

Fig. 6. Voltage fluctuations (time course) calculated at TS „C“ AC busbars (option 0).

Fig. 7. Load flow time course for TS „C“ (option 0).

Fig. 8. Voltage Total Harmonic Distortion (THD) calculated at TS „B“ AC busbars.

Fig. 9. Voltage flickers calculated at TS „B“ AC busbars and compared to criteria (option 0).

Fig. 10. Voltage flickers (time course) calculated at TS „B“ AC busbars (option 0).

Fig. 11. Load flow time course for TS „B“ (option 0).

There are presented in Figures 12 + 19 results for TS „B“ and TS „C“ with twelve-pulse rectifiers (tables 1b + 1b, Figure 3).

Fig. 12. Voltage Total Harmonic Distortion (THD) calculated at TS „C“ AC busbars (option 2).
Fig. 3. Traction substation supply system from AC busbars of a neighboring traction substation - (option 2) (D,E,F-new designed traction substations).

Basic parameters of the power supply system are shown in tables 1a + 1b.

Table 1a. Supply system parameters (option 0)

<table>
<thead>
<tr>
<th>TS</th>
<th>TSC</th>
<th>TSF</th>
</tr>
</thead>
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<tr>
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<tr>
<td>B</td>
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</tr>
<tr>
<td>C</td>
<td>3 x PK17</td>
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Tab. 1b. Supply system parameters (option 2)

<table>
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</tr>
<tr>
<td>C</td>
<td>2 x PD16</td>
<td>2 x PD16</td>
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1) Type and number of rectifier groups [-]
2) Supply system (S = PCC, TS = AC busbars of a neighboring traction substation)
3) Rated power of transformer 110/15 kV [MVA]
4) Short - circuit power (PCC-HV busbar) [MVA]
PK17-6-pulse; PD16-12-pulse

4. SIMULATION RESULTS

For option 0, simulation was performed assuming 3-hour peak period of traffic on the line. There are shown in Figures 4 - 7 results of simulations and analysis results obtained for the worst case - TS „C” AC busbars, which additionally supply TS „P” (results shown in Figures 8 + 11).

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Fig. 6. Voltage fluctuations (time course) calculated at TS „C” AC busbars (option 0).

Fig. 7. Load flow time course for TS „C” (option 0).

There are presented in Figures 12 + 19 results for TS „B” and TS „C” with twelve-pulse rectifiers (tables 1b + 1b, Figure 3)

Fig. 8. Voltage Total Harmonic Distortion (THD) calculated at TS „C” AC busbars.

Fig. 9. Voltage flickers calculated at TS „B” AC busbars and compared to criteria (option 0).

Fig. 10. Voltage flickers (time course) calculated at TS „B” AC busbars (option 0).

Fig. 11. Load flow time course for TS „B” (option 0).
4. MEASUREMENTS IN TSS

A set of measurements using a specialized equipment have been carried out in the operating traction substations with 6-pulse rectifiers. The results – 10 min RMS values are presented in the Figures 20-22 for a traction substation supplied by a short AC line.

In a case 12-pulse rectifiers are installed in TS there is practically now problems of THD U in a case ratio of a short-circuit level at AC busbars to load of TS is over 20-25 [4].

When this ratio is lower or resonance conditions are appearing (Fig. 25) THD U level at medium voltage may exceed limits defined by [3].(Fig.26), even the load of TS is low. But flickers of voltage (Fig. 27 i 28) are difficult to be overcome when medium voltage supply is applied and traction load high.

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In a case 12-pulse rectifiers are installed in TS there is practically now problems of THD U in a case ratio of a short-circuit level at AC busbars to load of TS is over 20-25 [4].

When this ratio is lower or resonance conditions are appearing (Fig. 25) THD U level at medium voltage may exceed limits defined by [3] (Fig. 26), even the load of TS is low. But flickers of voltage (Fig. 27) and 28) are difficult to be overcome when medium voltage supply is applied and traction load high.

Fig. 13. Voltage flickers calculated at TS „C“ AC busbars and compared to criteria used (option 2).

Fig. 14. Voltage flickers (time course) calculated at TS „C“ AC busbars (option 2).

Fig. 15. Load flow time course for TS „C“ (option 2).

Fig. 16. Voltage Total Harmonic Distortion (THD) calculated at TS „B“ AC busbars (option 2).

Fig. 17. Voltage flickers calculated at TS „B“ AC busbars and compared to criteria (option 2.1).

Fig. 18. Voltage flickers (time course) calculated at TS „B“ AC busbars (option 2).

Fig. 19. Load flow time course for TS „B“ (option 2).

Fig. 20 – THD U at 15kV AC bus-bars of a traction substation.

Fig. 21 – Flickers at 15 kV AC busbars.

Fig. 22 – 15 kV AC phase current.

while for a TS supplied by longer (8km) line in Figures 23 and 24.

Fig. 23 THD U at 15kV AC bus-bars of a traction substation.

Fig. 24 – 15kV AC phase current.

Fig. 25 – Harmonics at 15kV AC bus-bars of a 12-pulse traction substation (resonance conditions at AC side for 11-th and 13-th harmonics).

Fig. 26 – THD U at 15kV AC bus-bars of a 12-pulse traction substation (resonance conditions at AC side).
5. CONCLUSIONS

1. Modernization of the existing power supply of the electrified railway line system due to increase of traffic and rated power of locomotives create a need of undertaking feasibility studies of the technically possible design options.

2. The proposed solutions should not be technically adequate but as well justified by economic and financial analysis. This creates restrictions on the power supply modernization variants taking into account not only traction but as well power supply schemes.

3. Existing traction substations with 6-pulse rectifiers may cause significant harmonic distortions in supplying AC lines. The exchange them with 12-pulse rectifiers is a must not only in a case the power demand due to traffic increase is expected.

4. Schemes when two traction substations are supplied from the same AC busses of PCC is the worst case of charging the TS as harmonic distortions are cumulated. But in a case distances between traction substations are not so big (Fig.3) it may be technically and economically justified to connect them to the same PCC via AC busses of the neighboring substations, but only when they are equipped with 12-pulse rectifiers. Advantages of this scheme are:

- added power demand for two traction substations,
- no need to construct additional PCC.

while disadvantages:
- higher harmonic distortions and current changes (flickers) at AC busses of PCC.

3. The presented method, based on the derived simulation software makes a useful tool during a design process to assess the level of disturbances that this solution will cause. The results of simulations have been verified with the measurements in traction substations, as only the measurements in real operating conditions will give the answer about the level of harmonics and flickers are not exceeded.

4. The performed simulation and measurements in traction substations by the authors allow to state, that harmonic distortion problem at AC side of 3kV DC traction rectifiers substations may be overcome by installing 12-pulse rectifiers. But flickers caused by quick changes of traction currents are difficult to be limited when power demand is high and AC power supply system weak. The best, but the most costly solution is supplying of traction substations by high voltage (110kV) or dedication of MV AC busses only for traction needs.

REFERENCES


[3.] PN-EN Voltage characteristics of Electricity Supplied by Public Distribution Systems. 1998


SINGLE-PHASE POWER THEORY USING ORTHOGONAL TRANSFORMATIONS

Branslavs Dobrucký, Marek Roch, Wada M. Hoony

University of Zilina, Faculty of Electrical Engineering, Department of Power Systems and Electrical Engineering, ND 179, Zilina, Slovak Republic.

*University of East London, School of Electrical & Manufacturing Engineering, Department of Electrical and Electronic Engineering, Dagenham, Longbridge Road, London, RM2 5AS United Kingdom

Summary: The paper deals with the new method of power analysis of single-phase power electronic systems. Using a new particular transform theory the ordinary single-phase system can be transformed into equivalent two-axis orthogonal one. The new original thought is based on the idea that ordinary single-phase quantity can be complemented by fictitious second phase so that both of them will create orthogonal system, as is usual in three-phase systems. Application of the above theory makes this possible to use complex methods of analysis as instantaneous reactive power method, which have not been usable for single-phase systems so far. All types of the power, active and reactive, can be determined by this way.

1. INTRODUCTION

It is well known that the analysis of multiphase systems can be more simple using the Clarke/ Park transformation in two-axis stationary $(\alpha, \beta)$ or rotary $(q, d)$ reference frame. The above transformation can be used for electrical machines as well as for power electronic systems. The projection of time state-space vector for any quantity of symmetrical three-phase system in Gaus complex plane $(\alpha + j\beta)$ shows out six-side symmetry of vector quantity trajectory. Then, analysis of such a system can be focused on the interval equal to 1/6 of the time period only [1]-[3]. It is clear that when using similar transform of single-phase quantity into equivalent two-axes orthogonal system it will be possible to use all advantages as in three-phase transformed system with respect of 4-side symmetry instead of 6-side of previous[4].

2. USING ORTHOGONAL TRANSFORMATION FOR SINGLE-PHASE SYSTEM

As mentioned the basis for this approach can be symbolic vector expression and substitution of harmonic function, $\cos(\omega t) = \exp(j\omega t) \cdot \cos(\omega t) + j \cdot \sin(\omega t)$, (1) thus for resistant-inductive load current in steady-state $\mathbf{I}^* = U \exp(j\varphi) [Z \cdot \exp(j\varphi) + L \cdot \sin(\omega t)] \cdot R$, where $\varphi = \arccos(\alpha / R)$, (2) $Z = R + j \cdot L$, $I = U \cdot [R + j \cdot L]$, and $\varphi = \arccos(\alpha / R)$. The resulted current is simply the real part of $\mathbf{I}^*$, i.e.: $I^* = I \cdot \cos(\varphi)$. (3)

Assuming a single-phase system defined as in Fig. 1a $u(t) = U_0 \cos(\omega t)$, (4) Then after complementing by fictitious imaginary phase defined as in [4] by above approach as Fig. 1b $u(t) = U_0 \cdot \sin(\omega t) + j \cdot l = I \cdot \sin(\omega t)$, (5)

we obtain orthogonal co-ordinate system whereas $u_\alpha = u(t)$ and $u_\beta = u(t)$.

\[ u(t) = U_0 \cos(\omega t) + j \cdot l = I \cdot \sin(\omega t), \]

\[ I^* = I \cdot \cos(\varphi) \]

\[ Z = R + j \cdot L \]

\[ I = U \cdot [R + j \cdot L] \]

Note that both phases, real- and imaginary ones, are completely separated, however they are synchronised by signal SYNC, see Fig. 2. Such arrangement implies that zero component of any quantity will be a priori zero.

Generally, the fictitious phase can be created by shifting of ordinary single-phase quantity to the right with phase shift equal to $\pi / 2$. It follows out from the 4-side symmetry of vector quantity trajectory in Gaus plane [4].

Fig. 1a. Example of time-waveforms of voltage and current of the real phase.

Fig. 1b. Time-waveforms of voltage and current of the fictitious imaginary phase.