Data Article

Data from numerical analysis, simulation and experimental determinations performed to verify the sizing of an unbalanced capacitive compensator for three-phase four-wires networks

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A B S T R A C T

In a three-phase four-wire distribution network, the load unbalance can be compensated by the use of an unbalanced three-phase reactive compensator, containing six single-phase coils and capacitors, grouped into two distinct circuits, having Yn and delta connections. In (Pană et al., 2020) is presented a method of calculating the equivalent susceptances of the six reactive elements, so that they are capacitive or null. The paper demonstrates that a power factor improvement and a total or partial balancing of an unbalanced inductive load can be achieved by using an unbalanced capacitive compensator. The calculation method can be implemented in the control system of a SVC containing only single-phase capacitor banks. In this DiB article are presented additional data and information, obtained by numerical analysis, simulation-modeling and experimental determinations performed with the purpose of validation of the calculation method proposed in (Pană et al., 2020).

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1. Data

This article presents the numeric data used in and obtained by:

- numerical analysis (MathCAD),
- modeling and simulation software (Matlab-Simulink),
- experimental determinations in the laboratory.

These were performed with the purpose of validating the correctness of the mathematical model of calculating (sizing) method of the susceptances of an unbalanced capacitive compensator designed to power factor improvement and load balancing in a three-phase four-wire network. The method was presented in [1] and consists in determining the computation relations for the compensator susceptances, valid for nine possible types of load. The load types were defined based on the values of the load sequence current components, components targeted by the compensator action.

In addition to the data and information provided in [1], this paper presents data from the numerical analysis of unbalanced capacitive compensation for 14 (13) particular cases of the load structure. To highlight the influence of the load power factor and the relative values of the negative and zero sequence components on the load balancing level that can be obtained by unbalanced capacitive
compensation, all 14 (13) particular cases were chosen as belonging to type 1 of load, defined in [1]. The 14 (13) cases were divided into two groups as follows:

- the first group: the cases BCC1_1 ... BCC1_7, where the unbalanced loads have the same values of the phase active powers but different values of the phase reactive powers, so that:

$$\cos^{\text{load}} = 0.447...0.909, \quad k_{\text{ul}}^{\text{load}} = 0.42...0.51, \quad k_{0}^{\text{load}} = 0.179...0.037$$

- the second group: the cases BCC1_8 ... BCC1_14, where the unbalanced loads have different structures for both phase active and reactive power, but the same power factor. However, the unbalance levels are different:

$$\cos^{\text{load}} = 0.447 \quad k_{\text{ul}}^{\text{load}} = 0.42...0.188, \quad k_{0}^{\text{load}} = 0.179...0.08$$

The input and output data of the numerical analysis for the first group of particular cases are presented in Tables 1.1 - 1.5, and those for the second group are presented in Tables 2.1 - 2.5. The parameter and electrical quantities notes are the same as in [1] and the output data of the analysis corresponds to the same three-phase circuit sections:

- Section 1 - unbalanced load;
- Section 2 - Yn compensator;
- Section 3 - \( \Delta \) compensator;
- Section 4 - Yn+\( \Delta \) compensator;
- Section 5 - PCC.

Cases 1 and 8 of the load structure are the same. In fact, 13 particular cases of load were presented. The output data of the numerical analysis are practically identical to those obtained by modeling and simulation performed using the Matlab-Simulink. To demonstrate this statement, the models and the simulation data for only two of the particular cases are presented: the case of the load where BCC1_1 (identical to BCC1_8) was installed (Fig. 1) and the case of the load where BCC1_14 was installed (Fig. 2). In Fig. 3 are presented, face to face, the phase voltages and currents waveforms in the five analyzed sections, for the two particular cases modeled and simulated by Matlab-Simulink.

2. Experimental design, materials and methods

In order to demonstrate the correctness of the method of determination of the unbalanced capacitive compensator susceptances values respectively of the values obtained by power flow calculation (Mathcad) and modeling-simulation (Matlab-Simulink), experimental laboratory determinations were performed. For this purpose, only the particular case of BCC 5 use, defined in [1], which is more interesting than the others, because it allows totally load balancing, was considered.

The three-phase circuits were built based on the simplified electrical schema presented in [1]. The installation of the circuit elements and the recording equipment is shown in Fig. 4. The circuit elements have been adjusted so that the values of the equivalent parameters are as close as possible to those applied in the numerical study of normal operation regime for both unbalanced load and for BCC 5.

A power quality analyzer, type MAVOWATT 230, was used for measurements. Fig. 4 presents the electrical schema of the circuits built in the laboratory to perform experimental determinations. For the five sections of interest of the three-phase circuit, the following data were extracted in graphical form and they were included in [1]:
Table 1.1
Input data for numerical analysis of unbalanced capacitive compensation for the first group of particular load cases - Section 1 - Unbalanced load.

| Comp. Regime | BCC 1_1 | BCC 1_2 | BCC 1_3 | BCC 1_4 | BCC 1_5 | BCC 1_6 | BCC 1_7 |
|--------------|---------|---------|---------|---------|---------|---------|---------|
| [W] P_{load}^A | 200     | 200     | 200     | 200     | 200     | 200     | 200     |
| [W] P_{load}^B | 400     | 400     | 400     | 400     | 400     | 400     | 400     |
| [W] P_{load}^C | 1200    | 1200    | 1200    | 1200    | 1200    | 1200    | 1200    |
| [var] Q_{load}^A | 400     | 400     | 400     | 400     | 400     | 400     | 400     |
| [var] Q_{load}^B | 700     | 600     | 400     | 400     | 400     | 400     | 100     |
| [var] Q_{load}^C | 1300    | 1200    | 1100    | 800     | 600     | 500     | 400     |
| [H] Q_{load}^A | 0.439467| 0.585955| 0.878933| 0.878933| 0.878933| 1.757866| 3.515733|
| [H] Q_{load}^B | 0.251122| 0.292978| 0.439467| 0.439467| 0.439467| 0.439467| 1.757866|
| [H] Q_{load}^C | 0.13522 | 0.146489| 0.159806| 0.219733| 0.292978| 0.351573| 0.439467|
| [A] cos\{\varphi_{load}\} | 0.447214| 0.496139| 0.576883| 0.650791| 0.707107| 0.768221| 0.909065|
| [A] \theta_{load}^A | 1.903^{\pm0.43} | 1.534^{\pm0.37} | 1.204^{\pm0.45} | 1.204^{\pm0.45} | 1.204^{\pm0.45} | 0.952^{\pm0.57} | 0.877^{\pm0.74} |
| [A] \delta_{load}^A | 3.923^{\pm0.69} | 3.611^{\pm0.15} | 3.069^{\pm0.69} | 3.069^{\pm0.69} | 3.069^{\pm0.69} | 3.069^{\pm0.69} | 2.588^{\pm0.46} |
| [A] \beta_{load}^A | 5.788^{\pm4.1} | 5.383^{\pm4.2} | 4.981^{\pm4.9} | 3.806^{\pm4.3} | 3.069^{\pm4.9} | 3.069^{\pm4.9} | 2.407^{\pm7.5} |
| [A] \varphi_{load}^A | 3.806^{\pm0.43} | 3.431^{\pm0.26} | 2.952^{\pm4.7} | 2.615^{\pm4.9} | 2.407^{\pm4.5} | 2.216^{\pm3.9} | 1.872^{\pm2.4} |
| [A] \varphi_{load}^B | 1.598^{\pm136.67} | 1.598^{\pm136.67} | 1.645^{\pm141.41} | 1.225^{\pm138.43} | 0.949^{\pm135} | 0.923^{\pm126.46} | 0.954^{\pm146.31} |
| [A] \varphi_{load}^C | 0.42 | 0.466 | 0.557 | 0.469 | 0.394 | 0.46 | 0.51 |
| [A] \varphi_{load}^D | 0.681^{\pm62.77} | 0.681^{\pm62.77} | 0.681^{\pm50.9} | 0.328^{\pm78.43} | 0.254^{\pm125} | 0.393^{\pm40.36} | 0.069^{\pm146.31} |
| [A] \varphi_{load}^E | 0.179 | 0.198 | 0.233 | 0.126 | 0.106 | 0.177 | 0.037 |
| [A] \varphi_{load}^F | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Weighting factors
| k_0 | 0.381198 | 0.381198 | 0.352271 | 0.246619 | 0.154701 | 0.203302 | 0.037235 |
| k_A | 0.618802 | 0.618802 | 0.647729 | 0.753381 | 0.845299 | 0.796698 | 0.962765 |
| k_A | 0.937822 | 0.794678 | 0.761188 | 0.732051 | 0.574967 | 0.547967 | 0.382149 |
Table 1.2
Output data for numerical analysis of unbalanced capacitive compensation for the first group of particular load cases - Section 2 - Yn compensator.

| p. | Regime | Quantities | \(C^\text{Y}_1\) | \(C^\text{Y}_2\) | \(C^\text{Y}_3\) | \(C^\text{Y}_4\) | \(C^\text{Y}_5\) | \(C^\text{Y}_6\) | \(C^\text{Y}_7\) |
|----|--------|------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 1  | Compensator Yn | \(C^\text{Y}_1\) | 1.177463 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2  | | \(C^\text{Y}_2\) | 18.469082 | 16.216464 | 9.160849 | 8.774781 | 8.438896 | 9.942109 | 1.101328 |
| 3  | | \(C^\text{Y}_3\) | 33.085678 | 29.924232 | 25.356766 | 11.125976 | 2.261195 | 1.1775987 | 0.079072 |
| 4  | \(P^\text{Y}_1\) [W] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5  | \(P^\text{Y}_2\) [W] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6  | \(P^\text{Y}_3\) [W] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7  | \(Q^\text{Y}_1\) [var] | -20.428 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8  | \(Q^\text{Y}_2\) [var] | -320.428 | -281.347 | -158.936 | -152.238 | -146.410 | -172.490 | -19.107 |
| 9  | \(Q^\text{Y}_3\) [var] | -574.018 | -519.169 | -439.926 | -193.03 | -39.230 | -30.812 | -1.3719 |
| 10 | \(Q^\text{Y}_\text{tot}\) [var] | -914.875 | -800.515 | -598.861 | -345.267 | -185.641 | -203.302 | -20.479 |
| 11 | \(Q^\text{Y}_\text{av}\) [var] | -304.958 | -266.838 | -199.62 | -115.089 | -61.880 | -67.768 | -6.826 |
| 12 | \(I^\text{Y}_1\) [A] | 0.087\(^{30}\) | 0\(^{0}\) | 0\(^{0}\) | 0\(^{0}\) | 0\(^{0}\) | 0\(^{0}\) | 0\(^{0}\) | 0\(^{0}\) |
| 13 | \(I^\text{Y}_2\) [A] | 1.364\(^{-30}\) | 1.197\(^{-30}\) | 0.676\(^{-30}\) | 0.648\(^{-30}\) | 0.623\(^{-30}\) | 0.734\(^{-30}\) | 0.081\(^{-30}\) |
| 14 | \(I^\text{Y}_3\) [A] | 2.443\(^{-150}\) | 2.209\(^{-150}\) | 1.872\(^{-150}\) | 0.821\(^{-150}\) | 0.167\(^{-150}\) | 0.131\(^{-150}\) | 0.006\(^{-150}\) |
| 15 | \(I^\text{Y}_\text{av}\) [A] | 1.298\(^{90}\) | 1.135\(^{90}\) | 0.849\(^{90}\) | 0.49\(^{90}\) | 0.263\(^{90}\) | 0.288\(^{90}\) | 0.029\(^{90}\) |
| 16 | \(I^\text{Y}_\text{av}\) [A] | 0.681\(^{-62.77}\) | 0.638\(^{-62.77}\) | 0.547\(^{-50.9}\) | 0.25\(^{-78.43}\) | 0.186\(^{-135}\) | 0.226\(^{-140.36}\) | 0.026\(^{-146.31}\) |
| 17 | \(I^\text{Y}_\text{av}\) [A] | 0.681\(^{-117.23}\) | 0.638\(^{-117.23}\) | 0.547\(^{-129.1}\) | 0.25\(^{-101.56}\) | 0.186\(^{-145}\) | 0.226\(^{-39.64}\) | 0.026\(^{-33.69}\) |
### Table 1.3
Output data for numerical analysis of unbalanced capacitive compensation for the first group of particular load cases - Section 3 - Δ compensator.

| Comp. | Regime | Quantities | BCC 1.1 | BCC 1.2 | BCC 1.3 | BCC 1.4 | BCC 1.5 | BCC 1.6 | BCC 1.7 |
|-------|--------|------------|---------|---------|---------|---------|---------|---------|---------|
|       |        | $C_{B}$ [μF] | 0.637129 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2     |        | $C_{B}$ [μF] | 13.948224 | 12.48344 | 10.578038 | 10.132244 | 9.744397 | 7.653439 | 5.086817 |
| 3     |        | $C_{D}$ [μF] | 13.948224 | 12.48344 | 10.578038 | 10.132244 | 9.744397 | 7.653439 | 5.086817 |
| 4     |        | $P_{D}$ [W] | 200 | 187.564 | 158.936 | 152.238 | 146.410 | 114.993 | 76.43 |
| 5     |        | $P_{D}$ [W] | -200 | -187.564 | -158.936 | -152.238 | -146.410 | -114.993 | -76.43 |
| 6     |        | $P_{D}$ [W] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7     |        | $P_{D}$ [W] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8     |        | $Q_{D}$ [var] | -379.572 | -324.871 | -275.285 | -263.683 | -253.59 | -199.174 | -132.38 |
| 9     |        | $Q_{D}$ [var] | -379.572 | -324.871 | -275.285 | -263.683 | -253.589 | -199.174 | -132.38 |
| 10    |        | $Q_{D}$ [var] | -725.982 | -649.742 | -550.569 | -527.366 | -507.18 | -398.349 | -264.76 |
| 11    |        | $Q_{D}$ [var] | -1485.125 | -1299.485 | -1101.139 | -1054.733 | -1014.36 | -796.698 | -529.521 |
| 12    |        | $Q_{D}$ [var] | -495.042 | -433.162 | -367.046 | -351.578 | -338.12 | -265.566 | -176.507 |
| 13    |        | $P_{A}$ [A] | 1.826| 1.596 | 1.353 | 1.296 | 1.246 | 1.097 | 0.65 |
| 14    |        | $P_{A}$ [A] | 1.826 | 1.596 | 1.353 | 1.296 | 1.246 | 1.097 | 0.65 |
| 15    |        | $P_{A}$ [A] | 3.089 | 2.765 | 2.343 | 2.244 | 2.158 | 1.695 | 1.127 |
| 16    |        | $P_{A}$ [A] | 2.107 | 1.843 | 1.562 | 1.496 | 1.439 | 1.13 | 0.751 |
| 17    |        | $P_{A}$ [A] | 0.983 | 0.922 | 0.781 | 0.748 | 0.719 | 0.565 | 0.376 |
| 18    |        | $P_{A}$ [A] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

### Table 1.4
Output data for numerical analysis of unbalanced capacitive compensation for the first group of particular load cases - Section 4 - Yn+Δ compensator.

| Comp. | Regime | Quantities | BCC 1.1 | BCC 1.2 | BCC 1.3 | BCC 1.4 | BCC 1.5 | BCC 1.6 | BCC 1.7 |
|-------|--------|------------|---------|---------|---------|---------|---------|---------|---------|
|       |        | $P_{D}$ [W] | 200 | 187.564 | 158.936 | 152.238 | 146.410 | 114.993 | 76.43 |
| 2     |        | $P_{D}$ [W] | -200 | -187.564 | -158.936 | -152.238 | -146.410 | -114.993 | -76.43 |
| 3     |        | $P_{D}$ [W] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4     |        | $P_{D}$ [W] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5     |        | $P_{D}$ [W] | -200 | -324.871 | -275.285 | -263.683 | -253.59 | -199.174 | -132.38 |
| 6     |        | $Q_{D}$ [var] | -400 | -324.871 | -275.285 | -263.683 | -253.59 | -199.174 | -132.38 |
| 7     |        | $Q_{D}$ [var] | -700 | -606.218 | -434.22 | -415.921 | -400 | -371.664 | -151.488 |
| 8     |        | $Q_{D}$ [var] | -1300 | -1168.911 | -990.495 | -720.396 | -564.41 | -429.161 | -266.132 |
| 9     |        | $Q_{D}$ [var] | -2400 | -2100 | -1700 | -1400 | -1200 | -1000 | -550 |
| 10    |        | $Q_{D}$ [var] | -800 | -700 | -566.667 | -466.667 | -400 | -333.333 | -183.333 |
| 11    |        | $P_{L}$ [A] | 1.903 | 1.596 | 1.353 | 1.296 | 1.246 | 1.097 | 0.65 |
| 12    |        | $P_{L}$ [A] | 3.089 | 2.765 | 2.343 | 2.244 | 2.158 | 1.695 | 1.127 |
| 13    |        | $P_{L}$ [A] | 5.532 | 4.974 | 4.215 | 3.066 | 2.325 | 1.826 | 1.132 |
| 14    |        | $P_{L}$ [A] | 3.404 | 2.979 | 2.411 | 1.988 | 1.702 | 1.418 | 0.78 |
| 15    |        | $P_{L}$ [A] | 1.598 | 1.499 | 1.307 | 0.933 | 0.695 | 0.531 | 0.365 |
| 16    |        | $P_{L}$ [A] | 0.681 | 0.638 | 0.547 | 0.547 | 0.25 | 0.186 | 0.026 |
The currents distortion come from the network and the non-linearity of the autotransformer. However, the total harmonic distortion of the phase voltages does not exceed 4%. The currents distortion.

Experimental determinations were performed in conditions more or less close to ideal ones, in which the calculation and simulation were done as follows:

The power supply of the circuit was a three-phase autotransformer connected directly to the laboratory installation with a rated voltage of 230/400 V. Thus, due to both the supply network and the constructive unbalance of the autotransformer, the three-phase voltage set is neither symmetrical either as rms values and as phase shift. These non-symmetries are, however, very small. The percentage deviations from the reference values (values considered in numerical analysis and simulation) have the maximum values of 2.52% for rms values and 0.33% for phase shifts. The fact that the voltage asymmetries provided by the source used for experimental determinations can be neglected is also supported by the very small values of their negative and zero sequence components, which do not exceed the value of 0.6% relative to the positive sequence component.

The second cause of deviations of the values obtained by experimental determinations from those obtained by calculation, is the presence of voltages and currents harmonic regime. The voltage distortion mainly due to the network and the non-linearity of the autotransformer. However, the total harmonic distortion of the phase voltages does not exceed 4%. The currents distortion come from the

As expected, the data provided by experimental determinations are not identical to those provided by calculation (Mathcad) or simulation (Matlab-Simulink). In fact, simulation is based on numerical methods and algorithms for solving electrical circuits, so it is also a calculation. As it can be seen, between the data provided by the calculation and simulation, there is an almost perfect identity.
| Comp. | Regime | Quantities | BCC 1_8 | BCC 1_9 | BCC 1_10 | BCC 1_11 | BCC 1_12 | BCC 1_13 | BCC 1_14 |
|-------|--------|------------|--------|--------|--------|--------|--------|--------|--------|
| Load  |        | $p_{load}$ | [W]    |        |        |        |        |        |        |
| 1     | P loads |           | 200    | 250    | 200    | 250    | 200    | 250    | 300    |
| 2     | P loads |           | 600    | 600    | 600    | 600    | 600    | 500    | 500    |
| 3     | P loads |           | 400    | 350    | 400    | 350    | 400    | 450    | 400    |
| 4     | P loads |           | 1200   | 1200   | 1200   | 1200   | 1200   | 1200   | 1200   |
| 5     | P loads |           | 400    | 400    | 400    | 400    | 400    | 400    | 400    |

Input data for numerical analysis of unbalanced capacitive compensation for the second group of particular load cases - Section 1 - Unbalanced load.
Table 2.2
Output data for numerical analysis of unbalanced capacitive compensation for the second group of particular load cases - Section 2 - Yn compensator.

| Comp. | Regime | BCC 1_8 | BCC 1_9 | BCC 1_10 | BCC 1_11 | BCC 1_12 | BCC 1_13 | BCC 1_14 |
|-------|--------|---------|---------|---------|---------|---------|---------|---------|
|       |        | [μF]    | [μF]    | [μF]    | [μF]    | [μF]    | [μF]    | [μF]    |
| 1     | C_A   | 1.177463| 0.194723| 0.138366| 0.045619| 0.050755| 0.187513| 0.158093|
| 2     | C_B   | 18.469082| 12.494682| 17.429885| 12.345577| 11.578501| 16.706922| 11.685839|
| 3     | C_C   | 33.085787| 32.102938| 14.754962| 14.662215| 3.139605| 13.259685| 13.230264|
| 4     | P_A   | 0       | 0       | 0       | 0       | 0       | 0       | 0       |
| 5     | P_B   | 0       | 0       | 0       | 0       | 0       | 0       | 0       |
| 6     | P_C   | 0       | 0       | 0       | 0       | 0       | 0       | 0       |
| 7     | Q_A   | -20.428331| -3.378338| -2.400571| -0.791459| -0.880571| -3.253253| -2.742828|
| 8     | Q_B   | -320.42833| -216.775798| -302.400577| -214.18891| -200.88057| -289.85579| -202.74282|
| 9     | Q_C   | -574.01817| -556.968177| -255.99041| -254.38129| -54.47041| -230.04817| -229.53774|
| 10    | Q_tot | -914.87483| -777.122313| -560.79155| -469.36167| -256.23155| -523.15722| -435.02340|
| 11    | Q_A   | -304.958| -259.041| -186.931| -156.454| -85.4105| -174.386| -145.008|
| 12    | I_A   | 0.087 / 30° | 0.014 / 90° | 0.010 / 90° | 0.003 / 90° | 0.004 / 90° | 0.014 / 90° | 0.012 / 90° |
| 13    | I_B   | 1.364 / -30° | 0.922 / -30° | 1.287 / -30° | 0.911 / -30° | 0.855 / -30° | 1.233 / -30° | 0.863 / -30° |
| 14    | I_C   | 2.443 / -150° | 2.370 / -150° | 1.089 / -150° | 1.012 / -150° | 0.232 / -150° | 0.979 / -150° | 0.977 / -150° |
| 15    | I_Y   | 1.298 / 90° | 1.102 / 90° | 0.795 / 90° | 0.666 / 90° | 0.363 / 90° | 0.743 / 90° | 0.617 / 90° |
| 16    | I_V   | 0.681 / -62.77° | 0.686 / -52.47° | 0.397 / -98.26° | 0.335 / -81.52° | 0.254 / -135° | 0.371 / -101.41° | 0.304 / -83.79° |
| 17    | I_O   | 0.681 / 117.23° | 0.686 / 127.53° | 0.397 / 81.74° | 0.335 / 98.48° | 0.254 / 45° | 0.371 / 78.59° | 0.304 / 96.21° |
Table 2.3
Output data for numerical analysis of unbalanced capacitive compensation for the second group of particular load cases - Section 3 - Δ compensator.

| Comp. | Regime | Quantities | BCC 1_8 | BCC 1_9 | BCC 1_10 | BCC 1_11 | BCC 1_12 | BCC 1_13 | BCC 1_14 |
|-------|--------|------------|--------|--------|--------|--------|--------|--------|--------|
| Δ     | C_{ΔA} | [μF]       | 0.637129 | 0.102605 | 0.115444 | 0.03948 | 0.092444 | 0.105436 | 0.085545 |
|       | C_{ΔB} | [μF]       | 13.948224 | 13.413699 | 13.426538 | 13.350574 | 13.405358 | 6.760983 | 6.741092 |
|       | C_{ΔC} | [μF]       | 13.948224 | 10.085925 | 13.426538 | 10.022801 | 13.405358 | 10.088757 | 6.741092 |
|       | P_{ΔA} | [W]        | 200     | 150     | 200     | 150     | 200     | 150     | 100     |
|       | P_{ΔB} | [W]        | –200    | –200    | –200    | –200    | –200    | –200    | –100    |
|       | P_{ΔC} | [W]        | 50      | 50      | 0       | 50      | 0       | 50      | 0       |
|       | P_{Δ}  | [W]        | 0       | 0       | 0       | 0       | 0       | 0       | 0       |
|       | P_{Δ}  | [W]        | 0       | 0       | 0       | 0       | 0       | 0       | 0       |
|       | Q_{ΔA} | [var]      | –379.57166 | –265.148019 | –352.41881 | –261.86247 | –351.22169 | –265.29537 | –177.65753 |
|       | Q_{ΔB} | [var]      | –379.57166 | –351.75056 | –352.41881 | –348.46502 | –351.22169 | –178.69283 | –177.65753 |
|       | Q_{ΔC} | [var]      | –725.98138 | –611.585818 | –698.82897 | –608.27264 | –697.63185 | –438.50045 | –350.82626 |
|       | Q_{Δ}  | [var]      | –1485.1251 | –1228.45676 | –1403.6666 | –1218.6001 | –1400.0752 | –882.48867 | –706.17769 |
|       | Q_{Δ}  | [var]      | –495.042  | –409.486 | –467.889 | –406.2 | –466.692 | –294.163 | –235.393 |
|       | L_{Δ}  | [A]        | 1.826/60° | 1.296/60° | 1.724/60° | 1.284/60° | 1.72/60° | 1.297/60° | 0.868/60° |
|       | L_{Δ}  | [A]        | 1.826/60° | 1.722/60° | 1.724/60° | 1.71/60° | 1.72/60° | 0.871/60° | 0.868/60° |
|       | L_{Δ}  | [A]        | 3.089/150° | 2.611/154° | 2.974/150° | 2.597/154° | 2.969/150° | 1.878/143° | 1.493/150° |
|       | L_{Δ}  | [A]        | 2.107/30° | 1.742/30° | 1.991/30° | 1.729/30° | 1.986/30° | 1.257/30° | 1.002/30° |
|       | L_{Δ}  | [A]        | 0.983/30° | 0.886/43° | 0.983/30° | 0.886/43° | 0.983/30° | 0.65/10° | 0.491/30° |
|       | L_{Δ}  | [A]        | 0°      | 0°      | 0°      | 0°      | 0°      | 0°      | 0°      |
Table 2.4
Output data for numerical analysis of unbalanced capacitive compensation for the second group of particular load cases - Section 4 - Yn+Δ compensator.

| Comp. Regime | Quantities | BCC 1_8  | BCC 1_9  | BCC 1_10 | BCC 1_11 | BCC 1_12 | BCC 1_13 | BCC 1_14 |
|--------------|------------|----------|----------|----------|----------|----------|----------|----------|
| Compensator Yn + Δ | $P_{\text{comp}}^a$ [W] | 200 | 150 | 200 | 150 | 200 | 150 | 100 |
| | $P_{\text{comp}}^b$ [W] | -200 | -200 | -200 | -200 | -200 | -200 | -200 |
| | $P_{\text{comp}}^c$ [W] | 0 | 50 | 0 | 150 | 0 | -50 | 0 |
| | $P_{\text{tot}}$ [W] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^a$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^b$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^c$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^a_{\text{tot}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^b_{\text{tot}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^c_{\text{tot}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^a_{\text{av}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^b_{\text{av}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^c_{\text{av}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^a_{\text{tot}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^b_{\text{tot}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^c_{\text{tot}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^a_{\text{av}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^b_{\text{av}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^c_{\text{av}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^a_{\text{tot}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^b_{\text{tot}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^c_{\text{tot}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^a_{\text{av}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^b_{\text{av}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | $Q_{\text{comp}}^c_{\text{av}}$ [var] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
### Table 2.5
Output data for numerical analysis of unbalanced capacitive compensation for the second group of particular load cases - Section 2 - PCC.

| Comp. Regime | Quantities | BCC 1_8 | BCC 1_9 | BCC 1_10 | BCC 1_11 | BCC 1_12 | BCC 1_13 | BCC 1_14 |
|--------------|------------|---------|---------|----------|----------|----------|----------|----------|
| PCC          | $P_{\text{A}}^\text{PCC}$ [W] | 400     | 400     | 400      | 400      | 400      | 400      | 400      |
|              | $P_{\text{B}}^\text{PCC}$ [W] | 400     | 400     | 400      | 400      | 400      | 400      | 400      |
|              | $P_{\text{C}}^\text{PCC}$ [W] | 400     | 400     | 400      | 400      | 400      | 400      | 400      |
|              | $P_{\text{tot}}^\text{PCC}$ [W] | 1200    | 1200    | 1200     | 1200     | 1200     | 1200     | 1200     |
|              | $P_{\text{A}}^\text{PCC}$ [var] | 0       | 131.473642 | 145.180614 | 237.346062 | 247.897735 | 331.451369 | 419.599633 |
|              | $P_{\text{B}}^\text{PCC}$ [var] | 0       | 131.473642 | 145.180614 | 237.346062 | 247.897735 | 331.451369 | 419.599633 |
|              | $P_{\text{C}}^\text{PCC}$ [var] | 0       | 131.473642 | 145.180614 | 237.346062 | 247.897735 | 331.451369 | 419.599633 |
|              | $P_{\text{tot}}^\text{PCC}$ [var] | 0       | 394.4209 | 435.5418 | 712.0382 | 743.6932 | 994.3541 | 1258.799 |
|              | $P_{\text{A}}^\text{PCC}$ [A] | 1.702/120° | 1.792/138.19° | 1.811/199.95° | 1.979/30.68° | 2.003/31.79° | 2.211/39.65° | 2.467/46.37° |
|              | $P_{\text{B}}^\text{PCC}$ [A] | 1.702/120° | 1.792/138.19° | 1.811/199.95° | 1.979/30.68° | 2.003/31.79° | 2.211/39.65° | 2.467/46.37° |
|              | $P_{\text{C}}^\text{PCC}$ [A] | 1.702/120° | 1.792/138.19° | 1.811/199.95° | 1.979/30.68° | 2.003/31.79° | 2.211/39.65° | 2.467/46.37° |
|              | $P_{\text{tot}}^\text{PCC}$ [A] | 0°       | 0°       | 0°       | 0°       | 0°       | 0°       | 0°       |
|              | $P_{\text{A}}^\text{PCC}$ [A] | 0°       | 0°       | 0°       | 0°       | 0°       | 0°       | 0°       |
|              | $P_{\text{B}}^\text{PCC}$ [A] | 0°       | 0°       | 0°       | 0°       | 0°       | 0°       | 0°       |
|              | $P_{\text{C}}^\text{PCC}$ [A] | 0°       | 0°       | 0°       | 0°       | 0°       | 0°       | 0°       |
Fig. 1. The model and simulation data of unbalanced capacitive compensation for the particular load case to which BCC 1_1(8) was installed.
Fig. 2. The model and simulation data of unbalanced capacitive compensation for the particular load case to which BCC 1_14 was installed.
Fig. 3. The phase voltages and currents waveforms of the three-phase circuit, in the five analyzed sections, for the particular load cases where a BCC was installed: 1_1 (8) and 1_14 respectively (Matlab-Simulink).
distorted supply voltages, but at the same time it is amplified due to the presence of non-linear circuit elements: single-phase ferromagnetic core coils used as inductive loads, respectively single-phase electrolytic capacitors used in the construction of the two three-phase compensators. However, the THD values for currents remained within reasonable limits, which did not exceed 15%.

The third cause of the deviations comes from the fact that the coils and capacitors intervene in the circuit, in addition to the reactive, dominant components, by their active components corresponding to the losses of active power produced in the windings, the ferromagnetic cores and the dielectric materials.

The fourth cause of deviations is itself the instrument of measurement. The Mavowatt 230 is actually a digital power quality analyzer. The measured voltages were acquired in a single node (at source) but in order to obtain the currents respective the powers in the five sections of the circuit, the measurements were repeated after the current clamps were moved. The measurement errors are very small, but especially in the case of currents, they are influenced by the rms measured values. It is known that measuring currents by using current transformers (current clamps) at much lower rms values than rated currents, the measurement errors are very high (even over ±5%). When measuring phase shifts (angles), errors are even greater. In addition, measured voltages and currents distortion leads to an additional increase in measurement errors.

To facilitate a direct comparison of experimentally obtained values with those obtained from the calculation they were grouped face-to-face in Tables 3.1–3.5. Also here it can be seen the percentages of deviations for all determined amounts.

Fig. 4. Circuit schema used in experimental determinations.
Table 3.1
Comparison between the values obtained by numerical analysis (simulation) and the values obtained by experimental determinations – Section 1 - unbalanced load.

| Component          | Regime | BCC 5 |
|--------------------|--------|-------|
|                    |        | Amounts | Ideal BCC (Mathcad, Simulink) | Real BCC (Experiment) | Deviation [%] |
| Unbalanced load    |        | Pload 1 | 300  | 299.77 | –0.74% |
|                    |        | Pload 2 | 500  | 490.39 | –1.92% |
|                    |        | Pload 3 | 1000 | 991.32 | –0.87% |
|                    |        | Pload 4 | 1800 | 1779.50 | –1.14% |
|                    |        | Pload 5 | 600  | 593.16 | –1.14% |
|                    |        | Qload 6 | [var]| 1000  | 1032.90 | 3.29% |
|                    |        | Qload 7 | [var]| 200   | 221.57  | 10.79% |
|                    |        | Qload 8 | [var]| 1500  | 1540.10 | 2.67% |
|                    |        | Qload 9 | [var]| 2700  | 2794.60 | 3.50% |
|                    |        | Qload 10| [var]| 900   | 931.53  | 3.50% |
|                    |        | cosθ  | –     | 0.5547 | –3.19% |
|                    |        | Pload 11|       | 4.539  | 4.670   | 2.89%/0.41% |
|                    |        | Pload 12| [A]   | 2.341  | 2.342   | –0.04%/-1.55% |
|                    |        | Pload 13| [A]   | 7.838  | 7.882   | 0.54%/–1.57% |
|                    |        | Pload 14| [A]   | 4.703  | 4.780   | 1.64% |
|                    |        | Pload 15| [A]   | 2.435  | 2.420   | –0.62% |
|                    |        | K load 16| [A]  | 0.518  | 0.507   | –2.12% |
|                    |        | Pload 17| [A]   | 1.06  | 1.09    | 2.64% |
|                    |        | Qload 18| [A]   | 0.226  | 0.227   | 0.58% |

Table 3.2
Comparison between the values obtained by numerical analysis (simulation) and the values obtained by experimental determinations – Section 2 – Yn compensator.

| Component          | Regime | BCC 5 |
|--------------------|--------|-------|
|                    |        | Amounts | Ideal BCC (Mathcad, Simulink) | Real BCC (Experiment) | Deviation [%] |
| Yn Compensator     |        | P V 1  | 0   | 0   | –0.173 | – |
|                    |        | P V 2  | 0   | 0.512 | – |
|                    |        | P V 3  | 0   | –0.114 | – |
|                    |        | P V 4  | 0   | 0.225 | – |
|                    |        | P V 5  | 0   | 0.075 | – |
|                    |        | Q V 6  | [var]| –116.26 | –115.08 | –1.01% |
|                    |        | Q V 7  | [var]| –9.08  | –9.24   | 1.76% |
|                    |        | Q V 8  | [var]| –789.46 | –797.71 | 1.05% |
|                    |        | Q V 9  | [var]| –914.80 | –922.03 | 0.79% |
|                    |        | Q V 10 | [var]| –304.93 | –307.34 | 0.79% |
|                    |        | I Y 11 | [A]   | 0.505  | 0.505   | 0%
|                    |        | I Y 12 | [A]   | 0.039  | 0.04/–0.04 | –2.56%/-9.33% |
|                    |        | I Y 13 | [A]   | 3.432  | 3.46/–3.46 | 0.82%/-0.07% |
|                    |        | I Y 14 | [A]   | 1.326  | 1.33    | 2.30% |
|                    |        | I Y 15 | [A]   | 1.062  | 1.07    | 0.75% |
|                    |        | I Y 16 | [A]   | 1.062  | 1.07    | 0.75% |
Table 3.3  
Comparison between the values obtained by numerical analysis (simulation) and the values obtained by experimental determinations – Section 3 – Δ compensator.

| Component Regime Amounts | BCC 5 Ideal BCC (Mathcad, Simulink) | Real BCC (Experiment) | Deviation [%] |
|--------------------------|-------------------------------------|-----------------------|----------------|
| Δ Compensator            | 1 \( P_A^\text{comp} \) [W]        | 300                   | 297.79         | −0.74%         |
|                          | 2 \( P_B^\text{comp} \) [W]        | 100                   | 111.35         | 11.35%         |
|                          | 3 \( P_C^\text{comp} \) [W]        | −400                  | −393.80        | −1.55%         |
|                          | 4 \( P_{\text{tot}}^\text{comp} \) [W] | 0                     | 15.34          | —              |
|                          | 5 \( P_{av}^\text{comp} \) [W]     | 0                     | 5.11           | —              |
|                          | 6 \( Q_A^\text{comp} \) [var]      | −883.74               | −115.08        | 0.58%          |
|                          | 7 \( Q_B^\text{comp} \) [var]      | −190.92               | −9.24          | 10.21%         |
|                          | 8 \( Q_C^\text{comp} \) [var]      | −710.54               | −797.71        | 1.13%          |
|                          | 9 \( Q_{\text{tot}}^\text{comp} \) [var] | −1785.20             | −922.03        | 1.83%          |
|                          | 10 \( Q_{av}^\text{comp} \) [var]  | −595.07               | −307.34        | 1.83%          |
|                          | 11 \( I_A^\text{comp} \) [A]       | 4.058                 | 0.50          | 1.28%          |
|                          | 12 \( I_B^\text{comp} \) [A]       | 0.937                 | 0.04          | 10.99%         |
|                          | 13 \( I_C^\text{comp} \) [A]       | 3.545                 | 3.46          | 0.42%          |
|                          | 14 \( I_{av}^\text{comp} \) [A]    | 2.587                 | 1.33          | 2.05%          |
|                          | 15 \( I_{\text{tot}}^\text{comp} \) [A] | 1.810                | 1.07          | −1.10%         |
|                          | 16 \( I_{av}^\text{comp} \) [A]    | 0.05                 | 1.07          | —              |

Table 3.4  
Comparison between the values obtained by numerical analysis (simulation) and the values obtained by experimental determinations – Section 4 – \( Yn + \Delta \) compensator.

| Component Regime Amounts | BCC 5 Ideal BCC (Mathcad, Simulink) | Real BCC (Experiment) | Deviation [%] |
|--------------------------|-------------------------------------|-----------------------|----------------|
| \( Yn + \Delta \) Compensator | 1 \( P_{A}^\text{comp} \) [W] | 300                   | 302.23         | 0.74%          |
|                          | 2 \( P_{B}^\text{comp} \) [W]     | 100                   | 112.85         | 12.85%         |
|                          | 3 \( P_{C}^\text{comp} \) [W]      | −400                  | −399.50        | −0.13%         |
|                          | 4 \( P_{\text{tot}}^\text{comp} \) [W] | 0                     | 15.59          | —              |
|                          | 5 \( P_{av}^\text{comp} \) [W]     | 0                     | 4.86           | —              |
|                          | 6 \( Q_{A}^\text{comp} \) [var]    | −1000                 | −1019.0        | −1.90%         |
|                          | 7 \( Q_{B}^\text{comp} \) [var]    | −200                  | −221.8         | 10.21%         |
|                          | 8 \( Q_{C}^\text{comp} \) [var]    | −1500                 | −1532.9        | 2.19%          |
|                          | 9 \( Q_{\text{tot}}^\text{comp} \) [var] | −2700               | −2773.8        | 2.73%          |
|                          | 10 \( Q_{av}^\text{comp} \) [var]   | −900                  | −924.6         | 2.73%          |
|                          | 11 \( I_{A}^\text{comp} \) [A]     | 4.539                 | 4.63          | 2.00%          |
|                          | 12 \( I_{B}^\text{comp} \) [A]     | 0.972                 | 1.08          | 1.11%          |
|                          | 13 \( I_{C}^\text{comp} \) [A]     | 6.750                 | 6.83          | 1.19%          |
|                          | 14 \( L_{\text{comp}} \) [A]       | 3.913                 | 4.01          | 2.48%          |
|                          | 15 \( L_{\text{comp}}^\text{var} \) [A] | 2.435               | 2.43          | −0.21%         |
|                          | 16 \( L_{\text{comp}}^\var \) [A]  | 1.062                 | 1.07          | 0.75%          |
Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Reference

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