Monitoring of medium voltage distribution networks by balance smart meters

Irina Golub[1,*], *Oleg* Voitov[1], *Evgeny* Boloev[1], and *Anatoly* Buchinsky [2]

[1]Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS), 664033, Irkutsk, Russia
[2]Regional State Unitary Energy Enterprise «Electric Grid Company for the operation of electric networks of Oblkommunenergo», 664009, Irkutsk, Russia

Abstract. This study addresses the issue of monitoring the unbalanced load flow of power distribution networks. To that end, instead of relying on medium voltage meters, we make use of balance smart meters installed on the low-voltage side of distribution transformers. We use a mathematical model of such transformers for real-time calculation of the powers and voltages on the medium voltage side.

1 Introduction

The load flow control of medium voltage (MV) distribution networks (DN) requires the operator to have accurate information about the state variables to ensure reliable, high quality, and economic operation of the system. Such applications that require current loading data rather than reference metering data or loading forecasts include reactive power and voltage regulation, network reconfiguration and reinforcement, and protective relaying and automatic controls.

Load unbalance in low voltage (LV) networks leads to unbalanced load flow of MV networks, thus requiring detailed three-phase modeling of the transmission lines and distribution transformers (DT) connecting the MV and LV networks. In order to estimate the parameter values of the state of the MV electrical network, one needs a software tool for load flow analysis of a three-phase unbalanced network based on measurement data and the availability of measurements in real time.

Load flow analysis of unbalanced networks can be performed by the SDO-7 software package, which introduces a single-line representation of three-phase lines, allowing the use of symmetrical load flow analysis programs for the unbalanced load flow analysis [1].

As far as direct measurements in LV networks are concerned, the load measurements available at individual nodes are not sufficient to ensure the observability of the DN. The substantial contribution of this study is that instead of measuring the loads and voltages on the primary side of the LV directly, we propose to calculate them through load monitoring by a balance smart meter (BSM) [2] on the secondary side of the LV DT. Such an approach proves effective due to the low cost of BSMs installed on the LV network as compared to devices installed on the MV network, and even more so when they are installed on both sides.

We performed a comprehensive analysis of the mathematical model of 6(10)/0.4 kV transformers used

in Russian DTs that rely on the Y/Y_0 arrangement of windings (wye-grounded wye). This allowed us to develop a simple algorithm for calculating loads and voltages on the primary side of DT. The algorithm showed, unlike what was reported in [3], that the total power losses were independent of the value of DT zero-sequence impedance. Furthermore, unlike the algorithm reported in [4], it did not require one to take into account the singularity of the block partitions of the DT nodal admittance matrix.

The calculations reported in this paper were performed for measurements made in a real-world DN and were validated against a measurement experiment on a physical model.

2 Model of a three-phase distribution transformer with the winding connection scheme Y/Y_0

Impedance values of windings of a three-phase DT winding reduced to the LV side are specified as a square matrix of impedances under the phase frame of reference Z_{abc} as obtained by the diagonal matrix Z_{120} of impedances of positive z_1, negative z_2, and zero z_0 sequences and the matrix A of transition from symmetrical components to the phase frame of reference

$$Z_{120} = \begin{pmatrix} z_1 & & \\ & z_2 & \\ & & z_0 \end{pmatrix}; Z_{abc} = AZ_{120}A^{-1};$$

$$A = \begin{pmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{pmatrix}; a = \ell^{j\frac{2\pi}{3}}. \quad (1)$$

The impedance matrix Z_{abc} is used to arrive at the admittance matrix of the transformer windings $Y_t = Z_{abc}^{-1}$.

When modeling a DT, we assume that its primary winding is reduced to the secondary winding. The reduced currents I_1° on the primary side and currents I_2

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* Corresponding author: golub@isem.irk.ru

on the secondary side of the DT, can be determined by the matrix of nodal admittances Y_{Y/Y_0}, the reduced voltage on the primary side U_1°, and the voltage on the secondary side U_2 as reported in [5,6]

$$\begin{pmatrix} I_1^\circ \\ I_2 \end{pmatrix} = \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix} \begin{pmatrix} U_1^\circ \\ U_2 \end{pmatrix} = Y_{Y/Y_0} \begin{pmatrix} U_1^\circ \\ U_2 \end{pmatrix}. \quad (2)$$

The structure of block partitions of the nodal admittance matrix is determined by the winding connection scheme Y/Y_0, for which, as shown in [5], block partitions Y_{11} and Y_{22} completely coincide, and block partitions Y_{12} and Y_{21} coincide with them while having the opposite signs, with all blocks being singular

$$Y_{11} = Y_{22} = \frac{1}{3} \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} Y_t;$$

$$Y_{12} = Y_{21} = \frac{1}{3} \begin{pmatrix} -2 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{pmatrix} Y_t. \quad (3)$$

3 Algorithm for calculating voltages and powers on the primary side of the DT by measurements coming from BSMs installed on the secondary side

We assume that active and reactive powers and voltages on the primary side of the DT are to be determined by snapshots [a] of measurements of average phase values of active and reactive powers and voltage magnitudes relative to the neutral point, as performed by a three-phase BSM installed on the secondary side of the DT.

The voltage vector of the secondary winding of the DT can be represented as follows, according to the measurements of voltage magnitudes in phases *a, b, c* for each of the measurement snapshot:

$$U_2 = \begin{pmatrix} U_2^a \cdot (1 + j0) \\ U_2^b \cdot \left(-0.5 \cdot -j\sqrt{3/2} \right) \\ U_2^c \cdot \left(-0.5 + j\sqrt{3/2} \right) \end{pmatrix}. \quad (4)$$

Currents in the windings of phases f on the secondary side of DT are calculated by measuring phase values of active P_2^f and reactive Q_2^f power and voltage values U_2^f

$$I_2^f = \left(P_2^f - jQ_2^f \right) / U_2^{f\,*}. \quad (5)$$

In the case of unbalanced loading, voltages and currents contain positive, negative, and zero-sequence components [7].

The reduced current I_1° on the primary side of the transformer, as per expression (2), can be determined as

$$I_1^\circ = Y_{11} U_1^\circ + Y_{12} U_2. \quad (6)$$

The lack of grounding of the neutral point of the transformer primary winding results in the absence of symmetrical components of the zero-sequence in I_1°, while the voltages U_1° on the primary side of the transformer have positive, negative, and zero sequences.

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[a] Measurement snapshots mean a set of records of simultaneous readings of all SMs taken at a specified time interval separating individual records

The reduced voltage U_1° included in (6) can be found from the equation

$$U_1^\circ = (Y_{21})^{-1}(I_2 - Y_{22} U_2). \quad (7)$$

Since the matrix Y_{21} is singular, a regularization procedure [8] can be applied to obtain its inverse matrix, which is achieved by adding very small quantities to the diagonal entries of the matrix being inverted, thus simulating the introduction of shunts with small line-to-ground conductances in the ungrounded neutral point of the primary winding [4]. This approach can hardly be considered practical because of the large uncertainty of the resulting solution.

Another technique reported in [9] to overcome the singularity of the matrix Y_{21} is to determine the transformer U_1° primary side voltages omitting the zero-sequence component. Such a solution can be obtained by replacing the last row of the matrix Y_{21}, which is being inverted, with ones, and replacing the last row of the matrix Y_{22} and the last entry of the vector I_2 with zeros. Since the values of entries of the vector U_1° depend on the number of the row Y_{21} replaced by ones, in what follows we calculate their averages when adjusting each of the rows in (7), matrices Y_{21}, Y_{22}, and vector I_2 that correspond to phases *a, b, c*.

An alternative approach to obtaining the components of all three sequences for U_1° is to determine the voltage U_1° in the conventional way [7], i.e., by adding the voltage drop ΔU_{12} (defined as the product of the current I_2 and the matrix Z_{abc} of transformer winding impedances) to the voltage U_2.

$$U_1^\circ = U_2 + \Delta U_{12} = U_2 + Z_{abc} \cdot I_2. \quad (8)$$

An important result of comparing techniques (7) and (8) for determining the voltage U_1° is the complete coincidence of the positive- and negative-sequence components obtained therein. It should also be noted that the non-zero-sequence current I_1°, defined as (6), is independent of the way the voltage U_1° is calculated (i.e., without (7) or with (8) the zero-sequence component). Furthermore, the components of non-zero sequences of currents I_1° and I_2 coincide, which allows determining the current I_1° by removing the zero-sequence component from the current I_2 instead of using expression (6)

$$I_1^\circ = I_2 - \frac{1}{3}(I_2^a + I_2^b + I_2^c). \quad (9)$$

The currents and voltages obtained on the primary side of the transformer are used to determine the powers of the phase loads in the MV network

$$S_1^f = P_1^f + jQ_1^f = U_1^{\circ f} \cdot I_1^{\circ f\,*}. \quad (10)$$

When referring to equation (10), we will use the notation "without ZS" and "with ZS" to differentiate between the cases when it uses the voltage without and with the zero sequence, respectively.

There is no doubt that real-time calculation of loads with calculation intervals matching those of BSM measurements can prove a game-changer when compared to the use of control measurements or forecasts used to the same effect. The new approach enables load flow analysis in MV networks and its use as a foundation for solving a number of problems requiring knowledge of current load flow parameters.

Our research has shown that in order to determine the phase loads S_1^f on the primary side of the transformer according to BSM measurements on the secondary side of DT with the winding connection scheme Y/Y_0, average values of active P_2^f and reactive Q_2^f load powers and voltage magnitudes U_2^f, it is necessary to perform calculations as per the expressions indicated in brackets $I_2^f \rightarrow (5) \Rightarrow U_1^{\circ f} \rightarrow (8) \Rightarrow I_1^{\circ f} \rightarrow (9) \Rightarrow S_1^f \rightarrow (10)$.

Due to the lack of power and voltage measurements on the primary side of the transformer, one way to validate the solutions obtained in this way can be to compare the total active and reactive power losses in transformers Y/Y_0 with the losses calculated by the simple technique recommended in [10] and, according to the authors, validated against the results of numerous experiments on a physical model.

Ref. [3, 10] calculated the total power losses in transformers with winding connection scheme Y/Y_0 by positive, negative, and zero-sequence currents i_1, i_2, i_0 and impedances $r_1 + jx_1, r_2 + jx_2, r_0 + jx_0$ as follows

$$\Delta S = \Delta P + j\Delta Q =$$

$$= 3 \sum_{k=1,2,0} i_k i_k^* r_k + j3 \sum_{k=1,2,0} i_k i_k^* x_k. \quad (11)$$

The symmetrical components of the currents are determined from the phase currents on the secondary side of the transformer (2) as

$$i_{120} = A^{-1} I_2. \quad (12)$$

Another way to determine the power losses coinciding with those obtained using expression (11) is to calculate the total power losses under the phase frame of reference

$$\Delta S = I_2^T Z_{abc} I_2, \quad (13)$$

and power losses in phases *a, b, c*

$$\Delta S_{f=abc} = (z_f \cdot I_2) \cdot I_2^*, \quad (14)$$

where z_f – row $f = abc$ of matrix Z_{abc}. The powers on the primary side of the transformer, taking into account (13), can be determined as follows

$$S_1^f = P_1^f + jQ_1^f = S_2^f + \Delta S_{f=abc}. \quad (15)$$

4 A case study of calculating MV network loads from BSM

We used 1,344 30-minute snapshots of measurements of active and reactive powers and voltage magnitudes to demonstrate how to calculate powers on the primary side of DT. The measurements were made by a three-phase BSM connected on the secondary side of DT 10/0.4. The DT had a nominal capacity of 160 kVA and served single-phase and three-phase loads of 39 residential buildings of a real-word LV electrical network.

Fig. 1 shows the graphs of average phase values of active and reactive powers measured on the secondary side of DT for two days (96 measurement snapshots) and calculated on the primary side of DT by technique (10) employing two ways of calculating voltages U_1° (with ZS and without ZS). Despite the discrepancy between the phase power values obtained for the two ways of calculation on the primary side of the DT, the total active and reactive power values for the two ways of calculation were equal to each other.
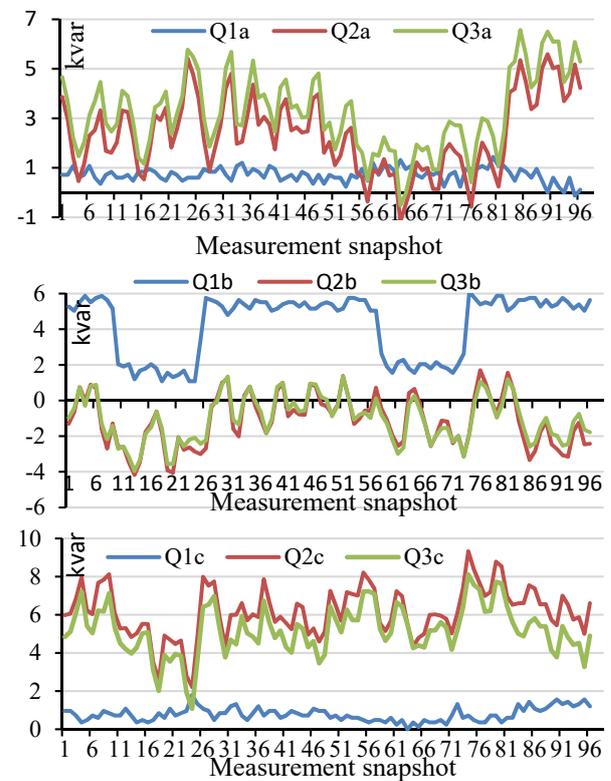

Fig. 1. Half-hourly average values of active and reactive powers in phases a, b, c: BSM -measured for two days - P1a, P1b, P1c, Q1a, Q1b, Q1c; as calculated on the primary side with ZS - P2a, P2b, P2c, Q2a, Q2b, Q2c and without ZS - P3a, P2b, P3c, Q3a, Q3b, Q3c.
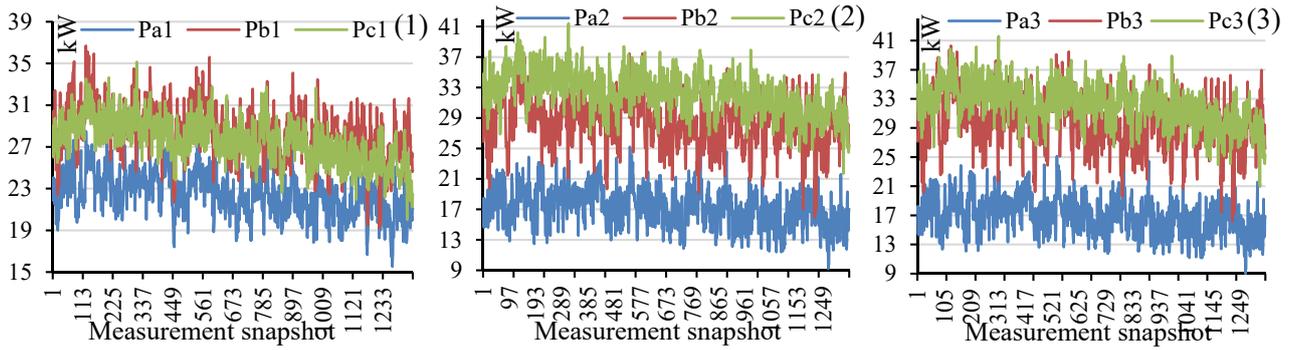
Fig. 2. Half-hourly average values of active powers in phases a, b, c,(1) - as calculated on the primary side of DT with ZS - Pa1, Pb1, Pc1,(2)- as measured on the secondary side of DT - Pa2, Pb2, Pc2, (3) as calculated on the primary side of DT as per (15) - Pa3, Pb3,Pc3.
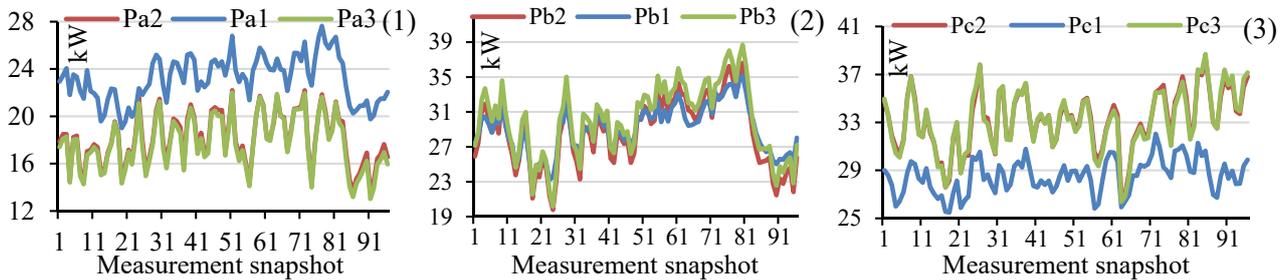

Fig. 3. Active half-hourly average values of powers in phases a, b, c: (1) as calculated on the primary side of DT with ZS - Pa1, Pb1, Pc1; (2) as measured on the secondary side of DT - Pa2, Pb2, Ps2; (3) as calculated on the primary side of DT as per (15) - Pa3, Pb3,Ps3.

To establish the relationship between the mismatched phase power values and the equality of their total values, Fig. 2 shows the graphs of active power in phases for 1,344 measurement snapshots during a month: 1) as calculated on the primary side with ZS; 2) as measured on the secondary side of the transformer; 3) as calculated on the primary side of the DT taking into account the power losses in phases as per (15).

Comparison of graphs 2.1 and 2.2 shows that redistribution of the total power of loads on the primary side of the DT with ZS led to their balancing, in which the power of the least loaded phase - *a* on the secondary side of the transformer increased, and the power of the most loaded phase - *c*, decreased. In the case of technique 2.3 for calculating the power on the primary side of DT with the use of power losses, there was no balancing of loads; on the contrary, the power of the least loaded phase *a* slightly decreased, and the power of the medium-loaded phase *b* increased.

Similar to Fig.2, Fig. 3 shows graphs of powers plotted for 96 first measurements out of 1,344 measurement snapshots, separately for each phase. They further confirmed the above conclusion that the calculation of power on the primary side of the

transformer as per expression (10) led, unlike the technique (15), to balancing of power values in phases.

The ability of the investigated DT model to make balancing of phase loads on its primary side, as shown by calculations, was confirmed by the results of the experimental measurements, during which a stepwise varying load was connected to the phases on the low side of the three-phase transformer TZS-1.5/1-380/36. Two "UF2M Power Quality Analyzers" were connected to the windings on the primary and secondary sides of the transformer. Vector measurements of magnitudes and phases of currents and voltages, as well as active powers were performed. The measurements were GPS-synchronized, with an averaging interval of 200ms, or 5 measurements per second. A total of 4,691 measurement snapshots were made, from which 15 groups were selected that included 5 measurements per second for active powers in the transformer windings on its primary and secondary sides. Fig.4 shows that balancing was achieved by flattening the loads on the primary side of the transformer for 15 groups of 5 measurements including 75 snapshots.
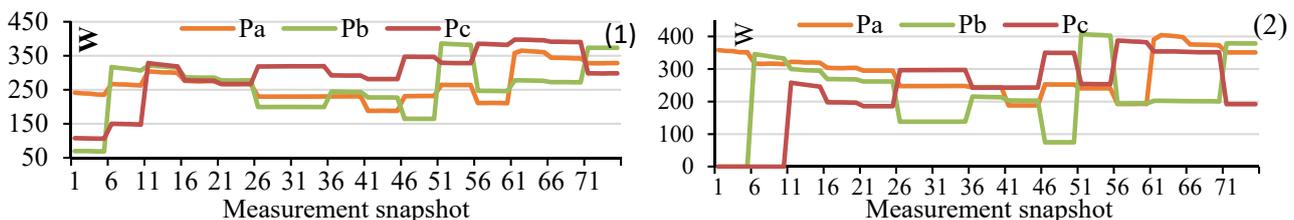

Fig. 4. 15 groups including 5 snapshots of measurements per second of active powers in transformer windings on its primary (1) and secondary sides (2).
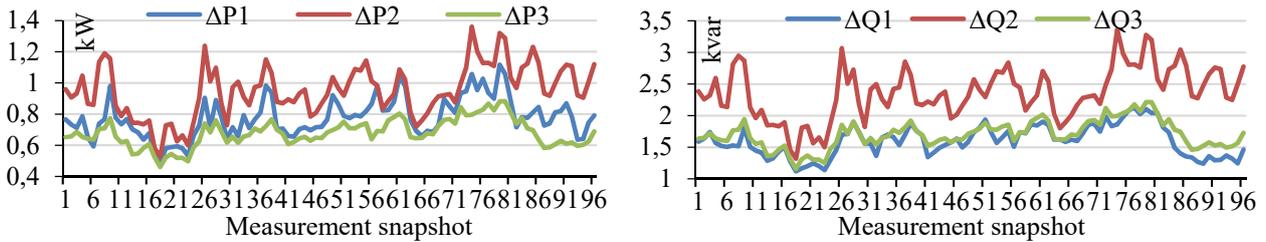
Fig. 5. Half-hourly total average values of active and reactive power losses for two days: ΔP1, ΔQ1 - losses obtained with the first technique; ΔP2, ΔQ2 - losses obtained as per expression (13) for nominal impedance values, and ΔP3, ΔQ3 - for zero-sequence impedance values reduced 10-fold.
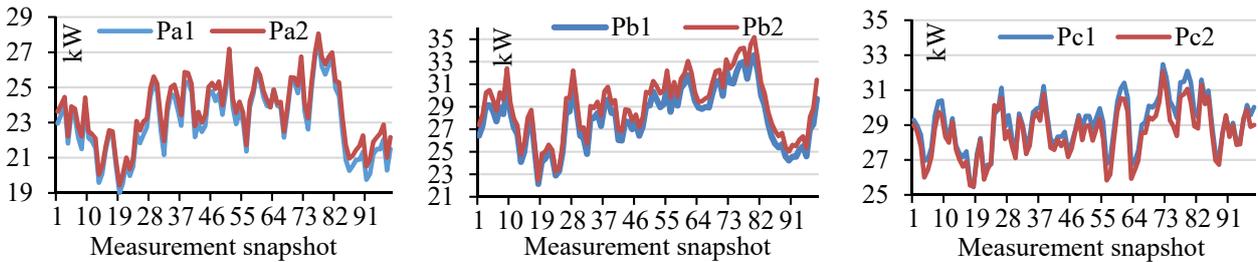

Fig. 6. Half-hourly average phase values of active powers with ZS, Pa1, Pb1, Pc1 corresponding to nominal values, and Pa2, Pb2, Pc2 with zero-sequence impedances increased 10-fold.

At the next stage of our study, we compared the total active and reactive power losses as calculated in two different ways: 1) as the difference of total power values calculated on the primary side of the DT and measured by BSM on its secondary side and 2) as total losses found as per expression (13) as recommended in [3,10].

In the case of applying the former technique, the total losses, similar to the total powers, did not change when the zero-sequence impedance was changed. The losses calculated as per the latter technique exceeded (in the case of standard zero-sequence impedance) or became less or equal (in the case of zero-sequence impedances reduced 10-fold) to the losses calculated as per the former technique, as shown in Fig. 5.

Fig. 6 shows how a change in zero sequence impedance, which did not affect the values of total power and total losses, led to a redistribution of total power between phases.

In what follows we show a load flow analysis performed for a real-world 10 kV MV DN fed from a 110/10 substation. The equivalent circuit of the DN, as presented in Fig. 7, contained 20 nodes. Eleven 10/04 DTs were connected to 9 of them and BSMs were installed on the LV side. The meters measured the load powers and voltage magnitudes at half-hourly intervals. The rated power of DT at node 15 was 400 kVA, nodes 19 and 20 were 250 kVA each, nodes 1 and 17 were 160 kVA each, nodes 5, 8, 16, and 18 were 100 kVA each, and nodes 4 and 9 were 63 kVA each.
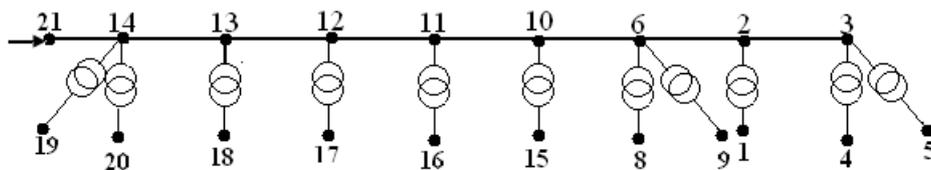

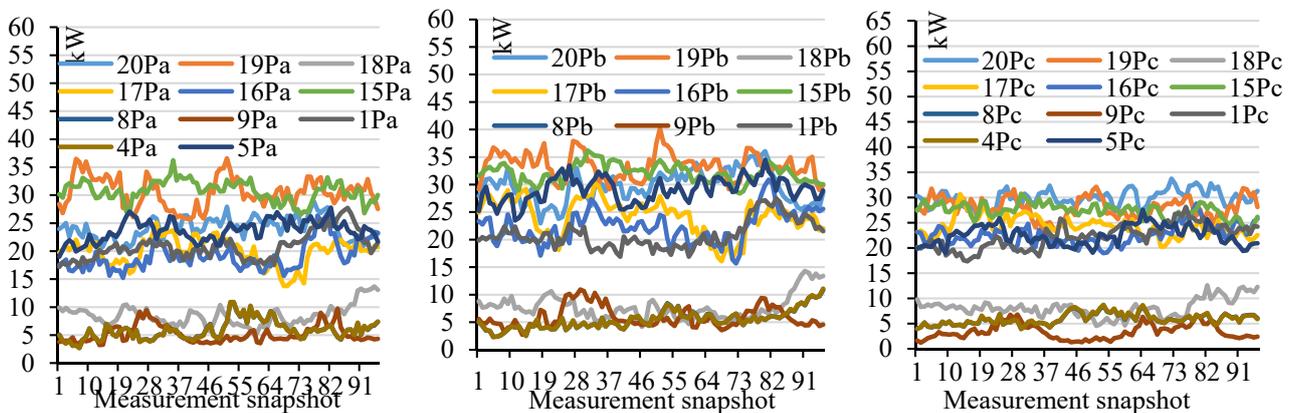**Fig. 7.** Schematic of the MV DN with DT 10/0.4 at nodes 5, 4, 1, 9, 8, 15 – 20.

Fig. 8. Half-hourly active powers of loads in the MV network in phases a, b, c as averaged over two days and obtained with ZS.
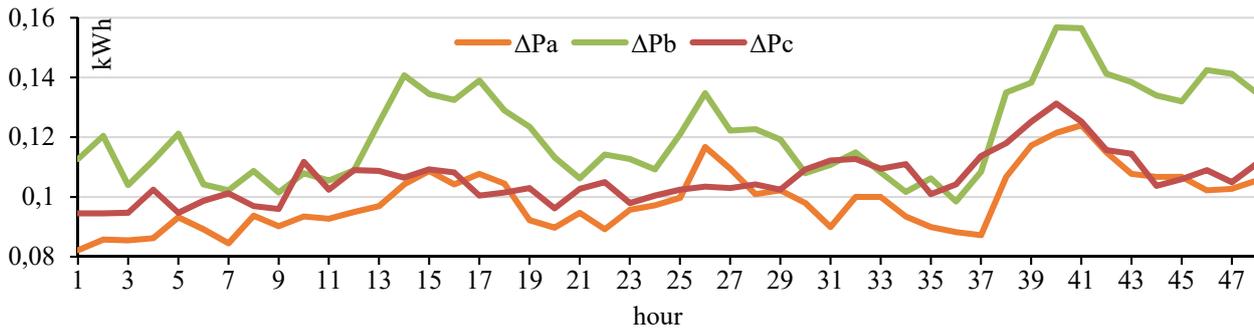
Fig. 9. Hourly power losses in the phases of the DN main wire for two days.

Fig. 8 shows the graphs of half-hourly average powers of active loads in the phases of the MV network, as calculated on the primary side of transformers. Similarly, the reactive powers of loads were obtained for each phase.

We relied on the SDO-7 [1] software package for load flow analysis in the unbalanced MV network (see Fig. 7) based on the values of active and reactive loads. To this end, Fig. 9 shows the values of average hourly active power losses in the phases of the main wire (which were equal to power losses per hour), as obtained from the load flow analysis for each hour for two days.

5 Conclusion

1. We proved experimentally the equality of non-zero components of voltage on the primary side of the DT for the cases when it was calculated both a) without considering the zero-sequence component and b) relying on the conventional technique of adding the voltage drop to the voltage on the secondary side of the DT, which allowed one to determine the zero-sequence component.

2. Our study showed that the total active and reactive powers on the primary side of the DT and the total power losses did not depend on either the zero-sequence component of the voltage or the value of the zero-sequence impedance of the DT.

3. The zero-sequence voltage component and the value of zero-sequence impedance affected the distribution of total active and reactive powers on the primary side between the phases of the DT.

4. Our calculations and an experimental measurement proved that calculation of loads on the primary side of the DT as the product of current and voltage led to balancing of phase loads as compared to loads on the secondary side of the DT.

5. We established that when the loads on the primary side were determined with the use of power losses calculated as the product of the matrix of self- and mutual impedances of the DT and the square of the current does it did not lead to the balancing of phase loads.

6. The efficacy of the contributed approach to calculating the loads on the primary side of the DT has been demonstrated through a case study of a real-world DN with 11 DTs, for which the load flow analysis was performed based on the loads on the MV side.

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