REDUCING ACTIVE ENERGY LOSSES IN LOW VOLTAGE DISTRIBUTION GRIDS

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Abstract – The paper presents the results of the implementation of a program for reducing technical active energy losses in the distribution network operated by Delgaz Grid DSO (Distribution System Operator). Measures applied to reduce technical losses addresses both transformers at the MV / LV transformer substations and the LV network power lines. The impact of these measures has been assessed using pilot networks with structures and electrical characteristics known in detail. For the phase load balancing measure two methods have been proposed, one based on a bottom-up constructive approach and the other based on identifying a (sub)optimal solution using meta-heuristic techniques.

Keywords: technical power and energy losses, grid losses reducing measures, voltage regulation, phase load balancing

1. INTRODUCTION

Most of electricity end users are connected to LV and MV distribution networks, which are powered by HV and VHV subtransmission and transmission networks. The distribution of the active power and energy losses between the different components of these networks respects the order of magnitude of the currents flowing through the conductors, depending on the rated voltage. Thus, the total power and energy losses in distribution networks are higher than those in transmission and subtransmission networks precisely because of lower values of rated voltages and higher currents. In this context, the reduction of active power losses in medium to low voltage distribution networks is of great importance. Thus, the literature specifies cases where up to 13% of the total power generated in the system is dissipated as power and / or energy losses in distribution networks [1].

Because the most part of the grid components and consumers have an inductive character, this results in the operation with an inductive power factor and negative effects on the voltage profiles and the level of power losses in distribution networks. In order to improve operating conditions, including the active power loss level, a number of methods can be applied, such as reactive power compensation and power factor improvement, voltage regulation, optimal network reconfiguration, phase load balancing, network reinforcement, or usage of high efficiency network components.

A review of the main aspects of reducing active power and energy losses in distribution networks by compensating reactive power using capacitor banks is presented in [2]. At the same time, paper [3] describes an original methodology for controlling reactive power compensation by dispatching capacitor banks installed in the distribution network. The optimal reconfiguration of distribution networks, also known as optimum grid unmeshing, aims at establishing network sectionalizing points that minimize active power or energy losses for certain network loading and operating conditions. For this purpose, a number of papers have been published in the literature, proposing different approaches, starting with traditional optimization techniques [4,5] and going to modern approaches based on meta-heuristic methods [6,7]. Some of these approaches are applied to traditional distribution network structures, while others treat the optimization methods in the presence of renewable sourses [7]. In other cases, the reduction of power losses is achieved by distributed reactive power compensation and voltage regulation, using the control capabilities of some microgenerators distributed in the network [8]. Redistributing consumers between phases to balance their load is another way of reducing active power losses in low-voltage distribution networks. This solution is presented in [9], where phase balancing uses fuzzy logic and a combinatorial optimization technique.

This paper presents the results of implementing a program to reduce the technical component of active energy losses in the LV distribution network operated by Delgaz Grid DSO in the eastern area of Romania. The program includes different measures such as resizing transformers from the MV/LV transformer substations considering actual load profiles, replacing transformers from the MV/LV substations with high efficiency transformers, voltage regulation in the LV distribution network using no load tap changer at MV/LV transformer substations, phase load balancing or network reinforcement. The paper includes also an approach to the phase-balancing problem based on optimization with a meta-heuristic method based on genetic algoritms.

2. THE PROGRAM TO REDUCE TECHNICAL ACTIVE ENERGY LOSSES

The active energy loss reduction program was launched starting 2012 and pursued two major objectives: (i) identifying and implementing effective measures to reduce active energy losses by upgrading and efficiently operating distribution networks, (ii) the establishment of pilot networks with structure, electrica land load characteristics specific to different sub-areas of the distribution network.

At the level of measures for reducing energy losses, the following categories were considered:

- resizing and interchanging transformers from MV/LV transformer substations according to their effective loading conditions, reffered as „Transformer Resizing";
- replacing transformers from MV/LV transformer substations with high efficiency transformers, reffered as „Efficient Transformers";
- voltage regulation in the LV distribution grid using no load tap changer at MV/LV transformer substations reffered as „Transformer Taps Control";
- phase load balacing by redistributing consumers between phases in the LV network, refered as „Phase Balancing";
- network reinforcement by increasing the conductors' cross-section in heavily loaded network areas, reffered as „Network Reinforcement".

Decisions on the application of the various loss reduction measures in the above list were made on the basis of the statistical analysis and processing of a set of load flow network measurements for the LV feeders in the transformer substations and for the LV transformer winding, as well as some voltage measurements at representative nodes in the network. Two categories of measurements were used:

- current and voltage intantaneous measurements for transformer substation and LV feeders, as phase and line voltages and phase currents;
- 1 day measurements, for transformer substation and LV feeders, as voltage and load profiles (currents, active and reactive powers, apparent powers) on phases.

Depending on the typical number of measures that are actually being applied, the number of measurements in the two categories may differ. For example, a typical structure of a measurement set, might be the following:

- 3000 instantaneous measurements, 500 on each county from the area controlled by the DSO;
- 1800 1-day measurements, 300 on each county from the area controlled by the DSO.

This measurement set structure will be used as a template to illustrate different categories of measures to reduce energy losses and their effects.

It is noted that the 1800 instantaneous measurements are used exclusively to select the location for three measures: „Transformer Resizing", „Efficient Transformers" and „Phase Balancing". For the „Transformer Taps Control" measure locations are selected directly based on information obtained from instantaneous measurements.

For the second major objective of the active energy losses reduction program, it was envisaged to set up pilot networks to study the effect of various measures to reduce energy losses based on off-line measurements and calculations.

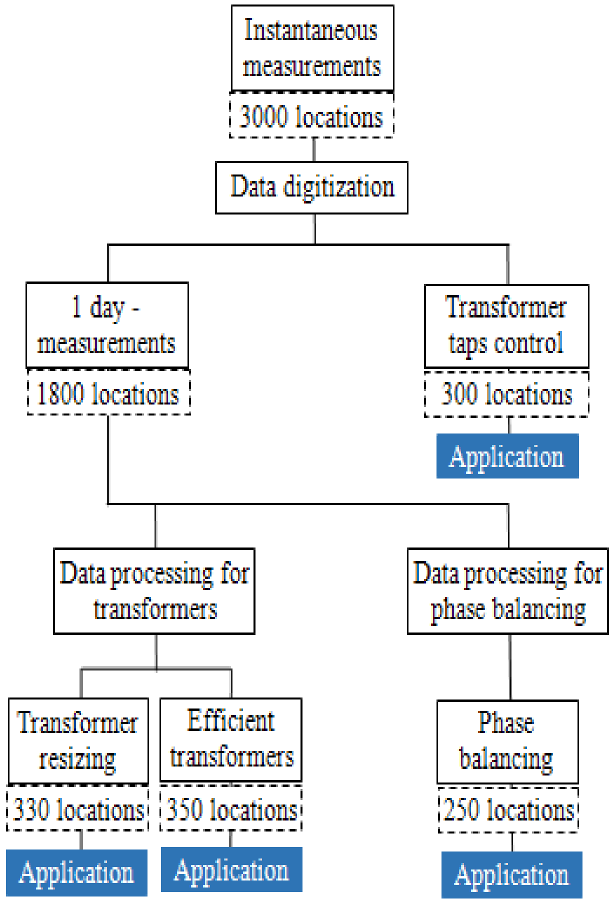


Fig. 1 - Diagram of measurement processing

The following sections show how to implement the two above-mentioned goals.

3. DATA PROCESSING

The data processing procedure for implementing energy losses reduction measures list is synthetically presented in Fig.1. Data processing begins by collecting a significant amount of instantaneous measurements made at transformer substations. To each transformer substation is associated a data form with measured voltage values (phase and line values) and current values (for each phase and the neutral wire). For the last measurement category , currents are monitored for each LV feeder and the whole substation. These measurements are made during peak hours and valley or off-peak hours.

To select locations for „Transformer Taps Control" program the following values are used as input data, taken from instantaneous measurements during off-peak hours: nominal power of the transformer substation (S_{nom} – kVA), the phase voltages at the LV busbars of the transformer substation ($U_{R\text{-}0}$, $U_{S\text{-}0}$ and $U_{T\text{-}0}$ – V), and currents on the general transformer, and on each phase ($I_{gen,R}$, $I_{gen,S}$ and $I_{gen,T}$). Based on these data, we also calculate:

- Estimated three-phase apparent power S_{est} (sum of apparent powers on the three phases, calculated as the product between phase voltage and phase current);
- Transformer loading coefficient (K_l=S_{est} / S_{nom}*100);

- Average voltage per phase ($U_{phase,avg}$ = ($U_{R\text{-}0}$ + $U_{S\text{-}0}$ + $U_{T\text{-}0}$)/3);
- The phase voltage value when changing the tap position by 2.5% ($U_{phase+2.5\%}$), or 5% ($U_{phase+5\%}$).

From these data the records for which the $U_{phase+5\%}$ and $U_{phase+2.5\%}$ fields exceed the value of the maximum allowable network voltage U_{max} are removed and after that the rest of data is sorted in decreasing order by the value of the K_I coefficient. Once more, the data for which K_I coefficient is not over the value of ε_I threshold are removed. Finally the data are sorted in increasing order by the phase voltage and from the new list the desired number of transformer substations to be included in the „Transformer Taps Control" program sre selected.

As sugested by the diagram in Fig. 1, for the other three active power losses reduction programs, first data from 1-day measurements are processed. These data come from locations that were established based on two criteria:

- Effective use or operation of transformers, with 50% weight and
- Phase load balancing for the LV distribution network, with 50% weight.

For the first criterion, measurements taken at peak hours are used, and transformers with rated power beyond a certain threshold value $S_{n,lim}$ (for example $S_{n,lim}$=160 kVA) and with loading coefficients either too low ($K_I < K_{min}$), or too high ($K_I > K_{max}$) are selected.

For the second criterion, based on the peak hours measurements the total current of the transformer (I_{PT} = $I_{gen,R}$ + $I_{gen,S}$ + $I_{gen,T}$) is selected and/or calculated and for each LV feeder, the average feeder current ($I_{d,avg}$ = ($I_{d,R}$ + $I_{d,S}$ + $I_{d,T}$)/3), the neutral current ($I_{d,0}$) and the average unbalance coefficient $N_{d,avg}$ is calculated using:

$$N_{d,avg} = \frac{I_{d,R}^2 + I_{d,S}^2 + I_{d,T}^2}{3 \cdot I_{d,avg}^2} \qquad (1)$$

Using this list, a selection procedure is applied to choose those feeders with an average unbalance coefficient and an average current over certain threshold values (N_{min}, respectively I_{min}).

To assess transformer energy losses for the „Transformer Resizing" program, data from 1-day measurements must be processed using a dedicated template (Fig. 2). This template uses hourly values of recorded currents, active and apparent powers on each phase and an average power factor to calculate load depenedent and no-load active power losses, for each sampling interval and for 4 types of transformers: one coreesponding to the existing type (marked in yellow in Fig. 2) and other three alternative resizing solutions (marked in blue in Fig. 2). For the alternative solutions losses are computed using catalog data for traditional transformers, from the same or similar generation in terms of the manufacturing technology.

For the „Efficient Transformers" program a similar template with the one from Fig. 2 is used, with the difference that the three alternative solutions marked in blue are chosen using the catalog data associated with high-efficiency transformers.

Locations selection for the „Transformer Resizing" and „Efficient Transformers" programs is done using data provided by the template files, as the one from Fig. 2, for each MV/LV transformer substation. These data are centralized to form a list of reference and resized (for interchange) transformers with their loss and loading data: nominal power (S_{nom}), annual load-dependent active energy losses ($dW_{s,an}$), annual no-load active energy losses ($dW_{g,an}$), total annual active energy losses (dW_{an}) and transformer loading coefficient (G_{tr}). The energy saving that is made by switching the reference transformer with the interchange one is calculated as the difference between the annual energy losses for both cases. Based on this value, it is possible to select from this list the optimal transformers' resizing solutions.

For the „Phase Balancing" program, data processing is made using a dedicated template file as the one in Fig. 3. For each feeder at the transformer substation, the values of the average phase current, the neutral wire current and the average unbalance coefficient, calculated with eq. (1), are stored. These data are centralized and organized at transformer substations and feeders level for processing. Amongst these feeders, those for which unbalance coefficient and the average phase current have values beyond certain threshold values (N_{min}, respectively I_{min}). To take account of the topological and electrical characteristics of the feeders, the single line diagrams provided with the instantaneous measurements are consulted and those feeders deemed innapropriate (e.g. too short or highly sized feeders) are excluded. From the final list the desired number of feeders to be included in the „Phase Balancing" program will be selected.

The application of „Phase Balancing" program was done using a method of rellocating consumers to phases by modifying the phase connection of the laterals from the main feeder (reffered as lateral re-phasing) and another rellocation method based on redistributing consumers to phases using a „bottom-up" constructive technique (reffered as consumers re-phasing) [10]. Also, to validate both methods in relation to the (sub)optimal problem solution, an optimal consumer phase rellocation method based on a meta-heuristic technique with genetic algorithms [12] was applied.

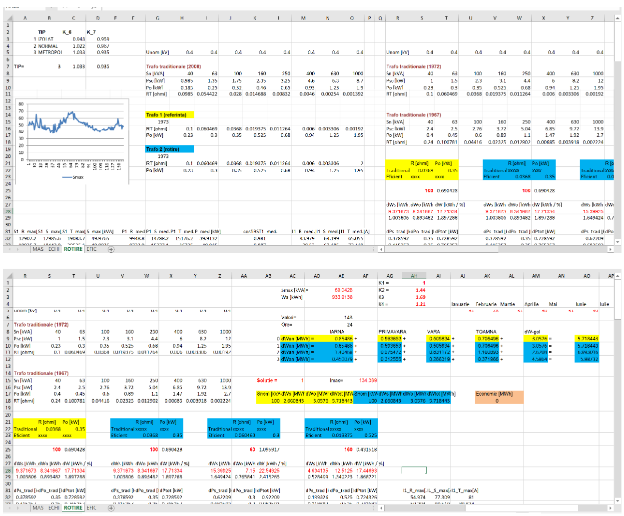


Fig. 2 - Template for data processing for „Transformer Resizing" and „Efficient Transformer" programs.

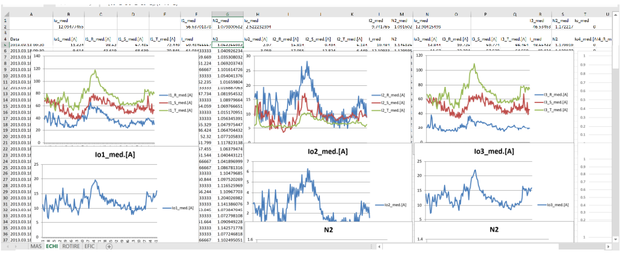


Fig. 3 - Template for data processing for the „Phase Balancing" program

4. GENETICAL ALGORITHMS

The proposed method for consumers re-phasing [10] aims at minimizing the unbalance coefficient at the entire network level using a bottom-up constructivist approach. The algorithm starts with the last pole on each LV feeder and stops after treating the first pole on the same feeder. For each pole, different consumers are connected using all possible combinations, and choosing amongst these that combination that leads to the minimum value of the objective function:

$$\min(\max(\Delta_R, \Delta_S, \Delta_T)) \tag{2}$$

where:

$$\Delta_R = \frac{i_R}{i_{av}} - 1; \quad \Delta_S = \frac{i_S}{i_{av}} - 1; \quad \Delta_T = \frac{i_T}{i_{av}} - 1; \tag{3}$$

and:

$$i_{av} = (i_R + i_S + i_T)/3 \tag{4}$$

To validate this method in relation with the (sub)optimal solution of the analysed problem, an optimization method based on meta-heuristic techniques can be used. Genetic algorithms (GAs) are meta-heuristic search techniques that are based on the principles of natural genetics and selection. A genetic algorithm describes a computational model that reproduces biological evolution to solve optimization problems. GA uses a set of possible solutions, reffered as population, represented as chromosomes and the biological selection, crossover and mutation operators [11]. During the evolutionary process, the quality of each chromosome is assessed using the value of the fitness function, aiming tp progressively refine the solutions, in search of the best one. Application of the GA is done within the steps described below:

Generate the initial population. At this step, a number of chromosomes that describe admissible solutions are randomly generated to create the initial population.

Selection. The selection operator assures the transfer of the most fitted chromosomes to the new generation using different techniques, the most common of which is the roulette rule or proportional selection [11]. In this case, different chromosomes are selected with a probability proportional to the value of their fitness function.

Crossover. For the aplication of this operator, two parent-chromosomes are first randomly selected, which will exchange information between them to create new addmissible solutions by changing some segments from their own structure. Generally, crossover can be applied in *n* points, but the most widespread variant is one-point crossover *(n=1)*.

Mutation. This operator randomly chooses a gene whitin a chromosome and change its value, satisfying certain variation limits and other specific problem constraints. This way, the diversity of the current population and the generation of new genetic information are encouraged.

	G_1	G_2	G_3	G_4	G_5		G_{nc-1}	G_{nc}
phase	3	2	2	1	3	....	1	2
type	1	0	1	1	1	....	1	0

Fig. 4 - Chromosome structure

For the problem considered in this paper, the representation of a possible solution is done using a chromosome with a lenght equal to the number of consumers in the network, nc , according to the model described in [12]. The genes of a chromosome can take values 1, 2, or 3, representing the phase to which the consumer is connected. For the highlinghting of three-phase consumers, an additional mask vector is used, whose elements are equal to 1 for single-phase consumers and 0 for three-phase consumers. Thus, the effective solution is obtained by multiplying element by element the chromosome vector with the mask vector. This representation is described in Fig. 4.

Using the coding of the consumers' network connection mode, as described by the chromosomal representation, the total load profiles for each phase are constructed:

$$P(t, ph) = \sum_{k \in S_{ph}} W(k) \cdot PT(t, c_k) \tag{5}$$

where: ph – phases R, S or T; $P(t,ph)$ – load at time t, on phase ph; S_{ph} – the set of consumers connected to the phase ph; c_k – the consumption class to which consumer k belongs; $PT(t,c_k)$ – load at time t, for the class type consumer c_k; $W(k)$ –daily energy consumption for consumer k.

The load profiles defined by eq. (5) are then used to define the objective function, as the maximum absolute error between the measured values of the load flows on the first section of the feeder for each phase and the values calculated above:

$$F = \max_{ph}(\max_{t}(abs(P(t, ph) - P^*(t, ph)))) \tag{6}$$

This objective function is to be minimized by the GA.

GA implementation also takes into account other problem constraints, such as the fact that a bi-phased or a mono-phased structure can be used on different sections of the feeder.

5. PILOT NETWORKS

Pilot networks definition and implementation have as a major objective the assement of the effects of different energy losses reduction measures, as mentioned above. The analysis was based on a series of case studies calculated for LV networks in 3 rural areas, reffered as PT1, PT2 and PT3. The networks supplied by the three transformer substations have a radial structure and the following features: PT1: 167 nodes, 2 feeders; PT2: 271 nodes, 3 feeders; PT3: 188 nodes, 3 feeders.

The study has not taken into consideration the urban networks because it has been found that under the actual conditions, the loading of these networks is low and very low (maximum loads between 100 and 110 kW, at a nominal power of 400kVA), the lenghts are short (several hundred meters) and conductors' cross-sections are large (up to 240 mm^2). These features make any of the active energy losses reduction measures ineffective.

The pilot networks study was developed in 4 main steps:

a) Weekly measurement campaigns (7days-measurements) for each transformer substation area and their analysis. Two issues were considered in this analysis. First, the balance between measured load flows and metered data gathered from balance meters in substations. Second, voltage profile analysis and phase loading balance analysis were considered.

b) Identifying topological and electrical characteristics of the networks (cross-sections, lengths, conductor types), consumers allocation on branches and phases, and generation of consumers load profiles based on readings provided by the SMART Metering system and the specific consumption profiles provided by the DSO. The resulting consumer profiles have been adjusted for energy balance validation at the transformer substation level.

c) Modeling the electricity LV networks and performing steady-state load flow calculation for each day of the analyzed week, for different assumptions, aiming to determine technical active energy losses.

d) Analysis of the load flow results from the technical losses reduction point of view (establishing possible solutions for loss reduction measures and assessing the effects of these measures).

The case studies developed for the pilot networks have considered three types of measures to reduce power and energy losses, namely: network reinforcement, phase load balancing, and voltage regulation using no load tap changing for MV/LV transformers. For each of these measures, the synthesis of the results obtained is indicated bellow.

5.1. Voltage regulation

For the voltage regulation measure, the selected pilot network was the one coresponding to PT1 area. The analysis of the load floe results in this network revealed an adquate level of voltage all over the network without any deviations from admissible values. As a result, the application of voltage regulation measure by changing transformer tap position with ±5% is not recommended. Instead, the effect of such a change can be simulated by changing the voltage value in the supply node (transformer substation LV busbars). In this way, it can be evaluated the effect of voltage increase from 0.95 p.u. (simulated situation) up to 1.00 p.u. (existing situation) on the reduction of technical active energy losses in the LV network. The simulation results, for network area supplied by PT1 are shown in Tabel 1.

Data from this table show that increasing the network voltage profile by changing the transformer's tap position from 0 to +5% causes a reduction of network energy loses for the study interval (one week) by 0.7%, from 5.7% to 5.0%.

Data from Table 1 show a reduction of energy losses durring a week, with a value of 281.9 kWh (5.7%) – 247.2 kWh (5.0%) = 34.7 kWh. This value can be extrapolated to a quartely level (34.7 kWh/week * 13 week/quarter =451.1 kWh/quarter) and then over a year (451.1 kWh/quarter. * [1+(1.1)^2+(1.2)^2+(1.3)^2)] = 2408.9 kWh/year), resulting in an annual energy saving of approx. 2.4 MWh. In the above computation scheme, the coefficients 1.1; 1.2 and 1.3 correspond to the change of the consumption level for each season of the year in relation to the reference season (summer), when the measurements were made in the network.

Table 1. Variation of technical losses in the LV PT1 network as a result of changing the transformer tap position.

Day	Load [kWh]	1.00*Un		0.95*Un	
		Losses		Losses	
		[kWh]	[%]	[kWh]	[%]
MO	676.0	34.3	4.8	39.0	5.5
TU	675.3	35.6	5.0	40.6	5.7
WE	656.0	34.1	4.9	38.8	5.6
TH	644.9	36.4	5.3	41.9	6.1
FR	662.6	32.7	4.7	37.1	5.3
SA	715.8	42.5	5.6	48.8	6.4
SU	664.8	31.6	4.5	35.7	5.1
Week	4695.4	247.2	5.0	281.9	5.7

5.2. Network reinforcement

For each feeder connected to the three transformer substations under consideration, the loading degrees of different network sections were assessed. The results are shown in Table 2. This table shows values for the first 15 sections of the feeders supplied from the three transformer substations. The loading degree was assessed by deviding the maximum current on one of the three phases to the maximum addmissible current coresponding to the conductor cross-section used on the respective feeder section.

The data show that the highest loading (67.8 %) was recorded at PT2, on the first section of one of the three feeders (BR 01). In all other cases , loading coefficients are under 50%. The feeder with the maximum loading 67.8% will be used to apply the network reinforcement measure to reduce technical losses.

Table 2. Maximum load on the first section of the feeders in the three pilot transformer substations (m- main branch; l – lateral branch).

Branch	PT 1			PT 2			PT 3		
	Type	Loading [%]	Cross-section [mm2]	Type	Loading [%]	Cross-section [mm2]	Type	Loading [%]	Cross-section [mm2]
BR 01	m	36.6	3*50+1*50	m	67.8	3*50+1*50	m1	36.5	3*50+1*50
BR 02	m	36.6		m	42.5	3*35+1*35	m1	36.4	
BR 03	m	36.6		m	42.5		m1	36.4	
BR 04	m	45.4	3*35+1*35	m	40.2		m1	31.5	
BR 05	m	45.4		m	40.2		m1	24.6	3*35+1*35
BR 06	m	45.4		m	40.2		m1	21.2	
BR 07	m	23.9		m	40.2		m1	20.2	
BR 08	m	23.9		m	38.9		m2	36	3*50+1*50
BR 09	m	23.9		m	35.5		m2	33.9	
BR 10	m	22.9		m	27.7		m2	33.5	3*35+1*35
BR 11	l	41.7		m	27.7		m2	32.7	3*50+1*50
BR 12	l	40.4		m	24.8		m2	31.5	
BR 13	l	40.4		m	22.2		m2	26.2	
BR 14	l	40.4		m	20.4		m2	26.2	
BR 15	l	39		m	20.4		m2	26.2	

Table 3. Energy losses reduction for PT2 area as a result of aplying the network reinforcement measure

Day	Energy losses				Load [kWh]
	[kWh]	[%]	[kWh]	[%]	
	Initial network		Reinforced network		
MO	48.9	4.1	41.2	3.5	1143.7
TU	45.9	3.9	38.8	3.3	1119.7
WE	44.0	3.9	37.1	3.3	1082.6
TH	47.4	4.1	39.7	3.5	1102.9
FR	48.8	4.1	40.9	3.5	1127.4
SA	77.9	5.5	63.9	4.5	1342.7
SU	44.4	3.9	37.4	3.3	1088.8
Week	357.3	4.3	299.0	3.6	8007.8

Network reinforcement consists in increasing the cross-section of conductors on certain network sections. Thus, for the selected feeder from PT2, the first section (BR 01) will change the conductors' cross-sections from 3*50+1*35 mm^2 to 3*95+1*50 mm^2. Also for the rest of sections on the main feeder (BR 02 – BR 15), consuctors' cross-sections will change from 3*35+1*50 mm^2 to 3*50+1*50 mm^2. As a result of these changes, the loading coefficient on the first section drops to 42.6%, and for the other sections the values drop below 30%. A new application of the load flow computation procedure for the new electrical characteristics shows a reduction of technical losses according to the data in Table 3.

Using the same calculation model as in the case of voltage regulation measure, active energy losses reduction over a week 357.3 – 299.0=58.3 kWh/week, can be generalized to a quarter (58.3 kWh/week*13 week/quarter=757.9 kWh/quarter) and to one year (757.9 kWh/quarter* [1+(1.1)^2+(1.2)^2+(1.3)^2)] = 4047 kWh / an) that is an annual energy saving of approx. 4.0 MWh.

5.3. Phase loading balancing

Another aspect of the analysis is the degree of imbalance of phase loading. To select the pilot network area for the application of this measure, the methodology described in the previous section has been used, based on measured currents and unbalance coefficients. The results of this evaluation for the three transformer substations considered in our analysis are shown in Table 4. Feeder selection was done using the thresold values: N_{min} =1.1 p.u. and I_{min}=20 A.

On the other hand, based on simulations, the end-nodes were identified (network nodes located at high electrical distances from the LV transformer busbars, with low values of the voltage). For these nodes, the paths to the source node were identified, and for some of the nodes on these paths the voltage variation profiles on the three phases were stored, to emphasize the degree of phase load imbalance. For example, Fig. 5 shows the weekly voltage variation profiles at the end-node 95 and for other two nodes on the path to this end-node, for a feeder supplied by PT3. Profiles from this picture suggest an excessive loading of phase S as compared to the other two phases.

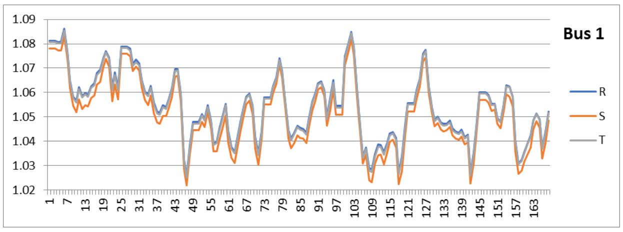
Analysing data presented in Table 4 and Fig. 5, one can recommend fedder 1 from PT3, with the end-node 95, as the most suitable one for testing the „Phase Balancing" measure.

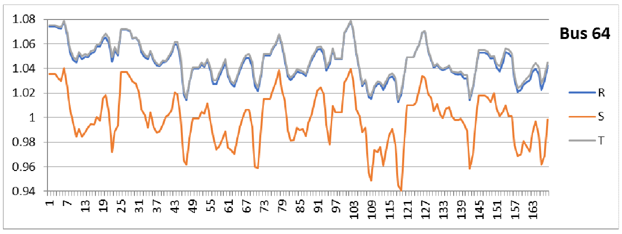
Table 4. Average currents and unbalance coefficients for general substation and feeders in the pilot networks.

MV/LV substation	General		Feeder 1		Feeder 2		Feeder 3	
	I_{med} [A]	N^2_{med}	I_{med} [A]	N^2_{med}	I_{med} [A]	N^2_{med}	I_{med} [A]	N^2_{med}
PT 1	42.72	1.11	23.10	1.08	17.87	1.07	n/a	n/a
PT 2	67.94	1.01	7.20	1.20	58.24	1.01	n/a	n/a
PT 3	62.82	1.02	22.13	1.10	34.35	1.07	2.55	2.79

Table 5. Comparison of network energy losses in the initial conditions and after the two consumers' phase rellocations.

Day	Load [kWh]	Initial allocation			Load reallocation-case 1			Load reallocation-case 2		
		Energy delivered [kWh]	Losses [kWh]	Losses [%]	Energy delivered [kWh]	Losses [kWh]	Losses [%]	Energy delivered [kWh]	Losses [kWh]	Losses [%]
MO	912.3	962.2	49.9	5.2	959.2	46.9	4.9	945.3	33.0	3.5
TU	1064.3	1131.8	67.5	6.0	1125.1	60.8	5.4	1108.4	44.1	4.0
WE	960.4	1012.6	52.2	5.2	1008.0	47.6	4.7	995.5	35.1	3.5
TH	941.4	996.1	54.7	5.5	991.0	49.6	5.0	977.2	35.8	3.7
FR	887.2	933.0	45.8	4.9	928.8	41.6	4.5	917.8	30.6	3.3
SA	984.2	1044.7	60.5	5.8	1038.0	53.8	5.2	1023.2	39.0	3.8
SU	828.2	868.3	40.1	4.6	865.4	37.2	4.3	855.7	27.5	3.2
Week	6578.0	6948.7	370.7	5.3	6915.5	337.5	4.9	6823.1	245.1	3.6





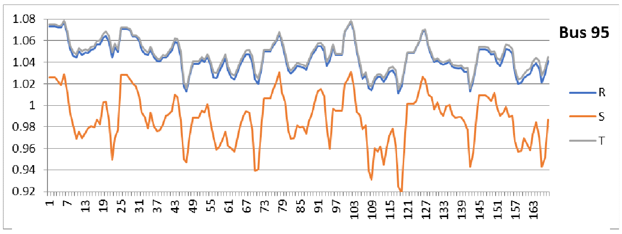


Fig. 5 - Weekly phase voltage variation (p.u., U_b=230 V) on the path to the end-node 95 (path 1-64-95), from PT3.

To study the effects of phase load balancing, two cases were taken into consideration: the initial situation (as a reference) and other two situations where consumers were rellocated on phases according to the models described in sections 3 and 4: Case 1 – rellocation by lateral re-phasing, and Case 2 – rellocation by consumer re-phasing.

The results of applying the two re-phasing procedures are synthetically described in Fig. 6 and Table 5. The load profiles in Fig. 6 shows that in Case 1, the consumers rellocation affects mainly the consumers connected to phases R and T, and less those connected to phase S. As a result the imbalances remain high for a value of a average unbalance coefficient of 1.19 p.u. Better results were obtained for the second rellocation case, when the value of the average unbalance coefficient decreases to 1.02 p.u. A similar behavior was also observed in the case of active energy losses. Thus, according to data in Table 5, one can see that the rellocation based on Case 1 (lateral re-phasing) provides an energy losses reduction during the analyzed interval (one week) of 0.4%, from 5.3% to 4.9%. This time too, the second procedure (consumers re-phasing) determines a more significant energy losses reduction, namely 1.7%, from 5.3% to 3.6%.

The extrapolation of these effects to a quarterly and annually level, based on calculations as described above, leads to the following values: 370.7 – 245.1=125.6 kWh/ week; 125.6 kWh/week*13 week/quarter=1632.8 kWh/ quarter, respectivelly 1632.8 kWh/quarter*[1+(1.1)^2 +(1.2)^2+(1.3)^2)]=8719.2 kWh/year, that means an annual energy saving of 8.7 MWh.

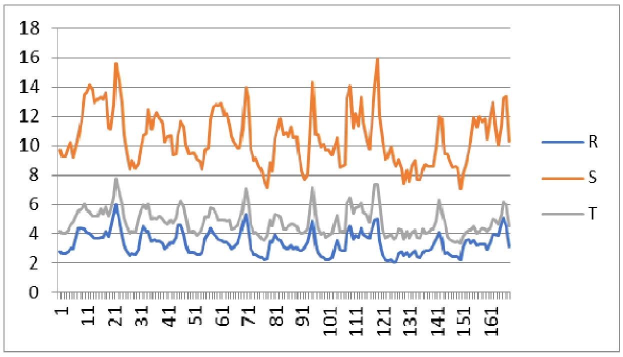
To validate the two consumer rellocation methods with respect to the (sub)optimal solution of the problem, this solution was determined using a GA optimization approach, according to the model described in section 4. It is mentioned that the objective function used by the GA was calculated with eq. (6) for the entire study interval, one week (t=168 hours). To take into account the stochastic character of this optimization method, the GA was applied using a set of 10 successive runs, and choosing the best solution. The results are shown in Table 6.

The comparison between data in Table 6 and Table 5, shows that the solution produced by redistributing the consumers using a bottom-up technique (consumer re-phasing) leads to a solution very close (from the point of view of active energy loss savings) to the one determined as a (sub)optimal solution by the GA. The difference between weekly active energy losses computed using the two approaches is just 10 kWh or 0.1%. For the (sub)optimal solution, energy losses decrease for six days of the week and increase insignificantly for Wednesday.

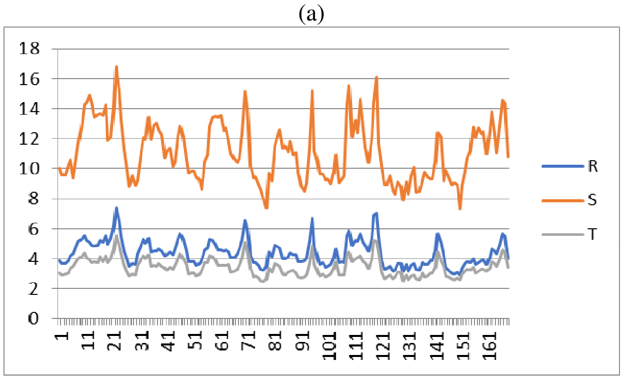
Consequently, for the effective application of the „Phase Balancing” program to reduce active power and energy losses, any of the two tested methods can be used with similar results with respect to the general loss level: the consumers re-phasing method and consumers redistribution using the GA.

Table 6. Comparison of network energy losses in the initial conditions and after consumer phase rellocation provided by the GA.

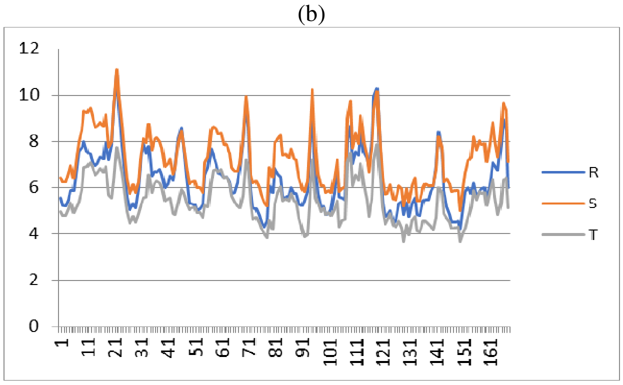
Day	Load [kWh]	Initial allocation			Load reallocation-GA		
		Energy delivered [kWh]	Losses [kWh]	Losses [%]	Energy delivered [kWh]	Losses [kWh]	Losses [%]
MO	912.3	962.2	49.9	5.2	943.7	31.4	3.3
TU	1064.3	1131.8	67.5	6.0	1106.5	42.2	3.8
WE	960.4	1012.6	52.2	5.2	995.7	35.3	3.5
TH	941.4	996.1	54.7	5.5	975.3	33.9	3.5
FR	887.2	933.0	45.8	4.9	915.8	28.6	3.1
SA	984.2	1044.7	60.5	5.8	1021.5	37.3	3.7
SU	828.2	868.3	40.1	4.6	854.6	26.4	3.1
Week	6578.0	6948.7	370.7	5.3	6813.1	235.1	3.5



(a)



(b)



(c)

Fig. 6 - Loading of the three phases on the first section of the feeder from PT 3 area (weekly load profile, in KW): (a) initial situation; (b) after the rellocation in Case 1 and (c) after rellocation in Case 2.

6. CONCLUSIONS

This paper presented the results of the implemention of a program meant to reducing technical active energy losses in the LV distribution grid operated by Delgaz Grid DSO. This program includes a series of measures related to the efficient operation of transformers from MV/LV substation (resizing according to actual loading conditions, use of high efficiency transformers and voltage regulation by changing transformers' tap position) or electrical lines (network reinforcement and phase load balancing). For the phase load balancing measure, two types of approaches were proposed: a solution based on a „bottom-up" constructive technique to redistribute consumers between phases and an approach that allows the identification of a (sub)optimal solution using a meta-heuristic GA-type technique. The results of loss reduction methods have been validated for a set of pilot networks, for which the specific impact of these measures has also been assessed.

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