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A CLUSTERING-BASED METHODOLOGY FOR PHASE LOAD BALANCING IN LOW VOLTAGE DISTRIBUTION NETWORKS

BY

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Abstract. A phase load balancing (PLB) methodology with clustering-based identification of the feeders with high unbalance degree is proposed. In the first stage, all feeders are classified into "importance" categories (*High*, *Medium*, and *Low*) using the K-Means clustering algorithm, considering the unbalance coefficient and total injected current in the peak load period. These categories will establish the ranking of low voltage (LV) distribution feeders subject to the balancing process. A PLB algorithm is applied in the second stage to identify the set of consumers connected to each feeder, assigned to an "importance" category, having phase load balancing device (PLBD) installed. Testing the methodology was done considering a database with 628 feeders for which there are the measurements of the phase and neutral currents. In the second stage, a LV feeder, assigned to the category with a *High* importance, was chosen to demonstrate the efficiency of the PLB algorithm. Although the percent of consumers equipped with this device is small, about 2% (3 consumers), the technical benefits were significant, quantified through an energy-saving in the analysed period (1 day) by 43.6%.

Keywords: energy efficiency; phase load balancing; clustering**.**

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1. Introduction

The European Union (EU) established in 2007 an ambitious energy plan, Strategic Energy Technology Plan (SET), starting from the idea that advanced energy technologies are essential in the fight against climate change and the security of the energy supply (European Commission, 2007). This plan focused on the following targets that had to be achieved by 2020, compared to the levels from 1990:

- reducing greenhouse gas emissions by 20%,
- increasing energy efficiency through the energy-savings by 20%,
- the total energy from renewable sources to be covered by 20%.

Aware of the technological challenges raised by these goals, the experts wish to accelerate the development and implementation of low-carbon technologies. At the same time, the research coordination and project funding contribute to the improvement of the existing technologies and costs reduction. The Energy Strategy of the European Commission adopted in February 2015 devotes one of its five dimensions to research, innovation, and competitiveness. Integrated into the SET-Plan, this will play a significant role in a new European approach regarding innovation and research, designed to accelerate the transition of current electricity grids into smart grids. These research directions were strengthened again by the EC Communication from 2018 (European Commission, 2018). The fight against climate change is one of the five main topics of the Europe 2030 strategy for smart, sustainable, and inclusive growth. The assumed targets of this strategy, at the 2030 level, compared to the year 1990, refer to a reduction by 40% of the greenhouse gas emissions, improving the energy efficiency by at least 32.5%, and coverage of at least 32% of the total energy from renewable sources.

The Distribution Network Operators (DNOs) identified a set of measures to achieve the target regarding energy efficiency, depending on the planning horizon: short-term measures, without investments, medium-term measures (assuming low investments), and long-term measures (requiring significant investments). Three action directions were identified in Romania by the DNOs to implement the energy efficiency measures: investments, efficient management of the electrical networks, and improving the electricity measurement (ANRE, 2014).

The phase load balancing (PLB) treated in the paper represents a measure belonging to the second action direction, namely the efficient management of the electrical networks, integrated by the DNOs into any planning horizon. If it is implemented manually with the help of the operative staff of the DNO, then it can be considered as a measure without investments. In this situation, the PLB process is done based on the voltage and current measurements from the electric distribution substations (EDS) on the LV side.

The allocations of consumers on the phases are obtained through an off-line PLB algorithm, and only the identified solution for the maximum value of the unbalance coefficient (UC) will be implemented in the network. The problem is that, due to loads of the single-phase consumers, which have a dynamic regime, the balancing scheme could not be valid at the next hour. But, this approach is a compromise between technical (the threshold imposed by DNO for the UC is 10%) and economic (minimum investment) criteria with satisfactory results (Grigoras *et al*., 2016a).

If the consumers have been integrated into the Smart Metering System (SMS), then the DNO can install a PLBD (Muhammad *et al*., 2016; Pakka *et al*., 2016; Tran *et al.*, 2017), which together with the smart meter (SM) compose smart balancing equipment leading to very high investments made by the DNO (Zheng *et al*., 2013; Ivanov *et al*., 2018; Homaee *et al*., 2019; Grigoras *et al*., 2020a). The SM communicates the values of the current and voltage toward the data concentrator from the EDS. The PLBD sends the connecting phase and the operation status, receiving from the concentrator the command to switch or not the consumer on the other phases. The solution identified with the PLB algorithm represents the base of the switching orders sent to the PLBDs. The measure can lead to a balancing regime where the unbalance coefficient is very close to the ideal case (1.0). However, the investments are high in this case, and the recovery inside the lifetime of equipment is uncertain (Grigoras *et al.*, 2020a).

In the paper, a clustering-based methodology consisting of two stages, having as the aim minimization of the unbalance degree in the LV distribution feeders using a reduced number of phase load balancing devices (PLBDs), has been proposed.

The main contributions are the following:

- Using the clustering techniques in the first stage to obtain the "importance" categories in the balancing process to establish the ranking for the feeders subject to the PLB process.
- The identification of consumers with the PLBD installed through a PLB algorithm that runs at the EDS level.

A database associated with 628 LV distribution feeders, containing the current measurements done in the peak load period, was considered in the clustering process to obtain the importance categories. The obtained results in the PLB process of a feeder from the category with a *High* importance highlighted that a reduced number of the PLBD installed at the consumers (3 from a maximum of 163 devices possible to be used) led to a value very close to the ideal target for the unbalance coefficient and the significant energy-saving.

The structure of the paper is the following: Section 2 highlights the importance of the clustering techniques in the decision-making on establishing the order in the PLB process of the distribution feeders and presents the stages for the implementation of the proposed PLB methodology, Section 3 details the results obtained in the case study, and Section 4 shows the conclusions and the future work.

2. Clustering-Based Methodology in Solving the Phase Load Balancing

The methodology uses two databases: the first corresponds to the current measurements on the LV side of the EDSs in the phase and neutral conductors, referred to as CM database, and the second holds the current curves of the consumers integrated into the SMS recorded in the peak load period, referred to as CC database. Fig. 1 presents the flowchart of the methodology.

The first stage of the methodology considers a clustering-based classification of the LV distribution feeders in the "importance" categories (*High*, *Medium*, and *Low*) to establish the order in the PLB process, which leads to increasing the technical benefits represented by the energy-saving.

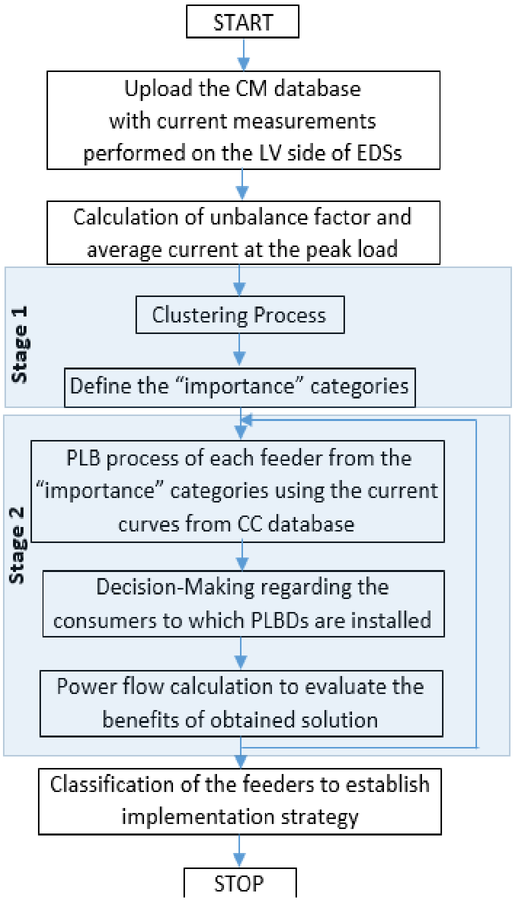

Fig. 1 – Flow-chart of the proposed methodology.

The unbalance coefficient and the average current, calculated using the values of phase currents from the CM database, are the features corresponding to the feeders used in the clustering process. The *High* importance is associated with the category where the unbalance coefficient and average current have the highest values. The *Low* importance is assigned to those categories with the average current having a low value, even if the unbalance coefficient is high.

In the second stage, feeders ordered according to the importance, from *High* to *Low*, are subject to the PLB process at the EDS level the using the proposed algorithm. Applying the PLB solution, the Decision-Maker (DM) can identify, also, the set of consumers that have smart integrated equipment from each feeder belonging to the imbalanced categories. The technical benefits are evaluated based on the power flow calculation. The following paragraphs present details on the two stages.

2.1. Stage 1. Clustering-Based Decision Making in the Classification of the Distribution Feeders

The clustering-based Decision-Making process has a structure consisting of steps' succession, which leads which leads to a high quality of the partitions. Thus, the steps are the following: built the database, obtaining the clusters (partitions), classification, evaluation of results, and developing the knowledge-based strategy (Hartigan, 2001).

The available records from the CM database belong to a population of n distribution feeders, $n = 1,\ldots, N$, described by m variables (the phase and neutral currents). Theoretically, the classification problem is simple. Because the database has a finite size, all possible partitions are generated based on a chosen criterion. This criterion refers to the used distance between elements. If the methods belong to the hierarchical clustering category, then the clusters are obtained based on:

- the minimum distance between the nearest elements of clusters (single-linkage method),
- the maximum distance between the clusters (complete linkage method),
- the average distances between all pairs of elements (average linkage method),
- the distance between the centroids of clusters (centroid method),
- the within-cluster sum of squares minimized for all partitions obtained through a merger of two clusters from the previous stage (Ward method).

The application of the above methods has the maximum effects for a small-size database (tens of elements) (Hartigan, 2001; Noroc and Grigoras 2020). For large-size databases, as is the case here, the K-means method will be used (Fränti and Sieranoja, 2019).

The principle of the K-means method consists in the minimization of the squared errors between the distances associated with each element and the centroid of the cluster (Grigoras *et al.*, 2016b; Fränti and Sieranoja, 2019):

$$\min(F) = \sum_{c=1}^{K}\sum_{l=1}^{n_c}\left\| e_l^c - m_c \right\|^2 \tag{1}$$

where: n_c is number of elements from cluster c; K represents the number of clusters; $\|e_l^c - m_c\|^2$ corresponds the distance between the element e_l^c ($l = 1, ..., n_c$) and the centroid m_c ($c = 1, ..., K$).

The steps used to obtain the partitions (clusters) are the following:

1. Introducing the number of clusters, K, and initialization the centroids $m_c^{(0)}$, $c = 1,\ldots, K$.

2. Distribution the samples $\{e\}$ among the each cluster c, $c = 1, \ldots, K$, in the current iteration, subject to the constraints:

$$e^{(i+1)} \in C_c^{(i+1)} \quad d\left(e^{(i+1)}, m_c^{(i+1)}\right) < d\left(e^{(i+1)}, m_c^{(i)}\right) \quad c = 1,\ldots, K \quad i = 0, 1,\ldots \tag{2}$$

where: $C_c^{(i+1)}$ represents the set of samples associated with the cluster c, having the centroid $m_c^{(i)}$ in iteration i.

3. Calculating the position of centroids corresponding to new clusters in the current iteration:

$$m_c^{(i+1)} = \frac{1}{n_c^{(i+1)}} \cdot \sum_{e \in C_c^{(i+1)}} e^{(i+1)}, \quad c = 1, 2, \ldots, K \quad i = 0,1,\ldots \tag{3}$$

where: $n_c^{(i+1)}$ is the number of elements from the cluster $C_c^{(i+1)}$ in iteration (i+1).

4. Steps 2 and 3 will be repeated until the position of the clusters does not modify, namely:

$$m_c^{(i+1)} = m_c^{(i)}, \quad c = 1, 2, \ldots, K \quad i = 0,1,\ldots \tag{4}$$

5. Verify the quality of the partitions. The most used test is based on the silhouette coefficient (Rousseeuw, 1987; Sinaga and Yang, 2020):

$$SC = \frac{1}{K}\sum_{c=1}^{K}\left(\frac{1}{n_c}\sum_{l=1}^{n_c}\left(\frac{d(e_l^c) - h(e_l^k)}{\max\{d_l, h_l\}}\right)\right) \tag{5}$$

where: $d(e_l^c)$ is average distance between element e_l^c and objects of the same cluster c; $d(e_l^k)$ is minimum average distance between the element e_l^k and elements from the closest cluster k to cluster c.

The maximum number of clusters, K_{max}, can be determined by the DM based on the relation (Grigoras, 2016b):

$$K_{\max} = \sqrt{N_f} \tag{6}$$

where: N_f represents the number of elements (feeders) form the database.

2.2. Stage 2. Phase Load Balancing

The PLB process uses an improved algorithm, presented in (Zheng *et al.*, 2013), based on the allocated phase and the hourly load of each consumer point uploaded from the CC database. Finally, the placement of the PLBDs will be at the consumers with the highest contribution in the PLB process. The PLB algorithm works at the LV level of the EDS, only for the feeders which have an unbalance coefficient higher than 1.1, based on the following steps:

1. Input the data regarding the allocated phase, hourly loads uploaded from the SMS database, and imposed threshold (*IT*) for the unbalanced coefficient;
2. Record the consumers in the vectors $[C_a]$, $[C_b]$, and $[C_c]$ and the phase currents, associated each consumer, in vectors $[I_a]$, $[I_b]$, and $[I_c]$, considering the allocation on the phases *a*, *b*, and *c*, having the sizes (N_ax1), (N_bx1), and (N_cx1), where N_a, N_b, and N_c represent the number of consumers on the three phases.
3. Calculate the total phase currents $I_a^{(t)}$, $I_b^{(t)}$, and $I_c^{(t)}$, $t = 1, \ldots, T$

$$I_a^{(t)} = \sum_{q=1}^{N_a} I_{a,q}^{(t)}\,, \quad I_b^{(t)} = \sum_{w=1}^{N_b} I_{b,w}^{(t)}\,, \quad I_c^{(t)} = \sum_{v=1}^{N_c} I_{c,v}^{(t)} \tag{7}$$

where: *T* represents the number of hours from the analyses period.

4. Calculate the unbalance coefficient with the relation (Grigoras *et al.*, 2020a; ANRE, 2016):

$$UC^{(t)} = \frac{1}{N_p} \cdot \sum_{ph\in\{a,b,c\}} \left(\frac{N_p \cdot I_{ph}^{(t)}}{\sum_{ph\in\{a,b,c\}} I_{ph}^{(t)}} \right)^2 \tag{8}$$

where: N_p represents the number of phases (in this case $N_p = 3$).

5. Identify the phases with maximum and minimum loading:

$$I_{ph,\max}^{(t)} = \max\left\{I_a^{(t)}, I_b^{(t)}, I_c^{(t)}\right\}; \quad I_{ph,\min}^{(t)} = \min\left\{I_a^{(t)}, I_b^{(t)}, I_c^{(t)}\right\},\; ph \in \{a,b,c\} \tag{9}$$

6. Identify the maximum value from the vector of the overloaded phase ($I^{(t)}_{ph,max}$) and the minimum value from the vector of the underloaded phase ($I^{(t)}_{ph,\,min}$) and interchange between them.

$$I_{ph,\max}^{(t)} = \{\{I_{ph,\max}^{(t)}\} - \{\max\{I_{ph,\max}^{(t)}\}\} \cup \{\min\{I_{ph,\min}^{(t)}\},\ ph \in \{a,b,c\} \quad (10)$$

$$I_{ph,\min}^{(t)} = \{\{I_{ph,\min}^{(t)}\} - \{\min\{I_{ph,\min}^{(t)}\}\} \cup \{\max\{I_{ph,\max}^{(t)}\},\ ph \in \{a,b,c\} \quad (11)$$

7. Modify the structure of consumers in the vectors [C_a], [C_b], and [C_c] considering the changes from Step 6.

8. Recalculation of the unbalance coefficient with relation (8).

9. If $UF > IT$, then return at Step 5, else display the results.

3. Case Study

Testing the methodology was done considering a CM database with the measured phase and neutral currents for 628 feeders in the peak load period in the first stage. The average current and the unbalance coefficient have been calculated using the phase currents. They represent the features of each feeder in the clustering process.

A pre-processing process has been initialized to identify the outliers (missing values for one, two, or all phases) that would negatively influence the clustering process. The weight of outliers was by 21% (129 missing values). After that, the data were normalized, using as normalized factors the maximum values of the current and the unbalanced coefficient, the clustering process has been initialized. The K-means algorithm ran for each value $K = 1, \ldots, K_{max}$, where K_{max}, determined with the relation (7), is 22.

After the quality test based on the silhouette coefficient, seven clusters have been obtained, representing the optimal solution for which the global silhouette coefficient had the maximum value (SC = 0.59). Fig. 2 highlights the quality of grouping where the clusters are well-shaped by the silhouette coefficients, and Fig. 3 offers additional information on the clustering process through a 2-D representation of the results associated with the optimal solution.

Table 1 presents a synthesis for each cluster represented through the statistical indicators (mean, standard deviation, maximum, and minimum values) of the features (average current and unbalance coefficient). The analysis of the data highlights high unbalances for all feeders from the obtained clusters. The mean of the unbalance factor is between 1.24 and 1.97, over the threshold (IT) by 1.1 aggregated by the DNO. Regarding the average current, the spread of mean is between 3.15 and 61.27A.

The classification of clusters in the "importance" categories intends to establish a PLB strategy with the maximum benefits on the increasing energy efficiency.

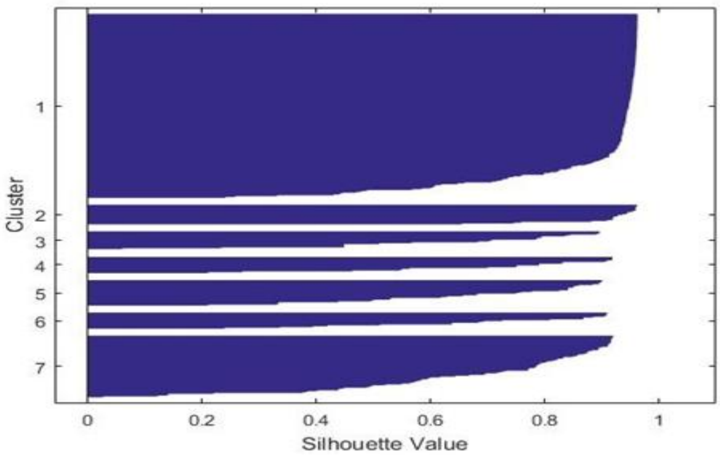

Fig. 2 – The value of silhouette coefficient for each cluster (K_{opt} = 7).

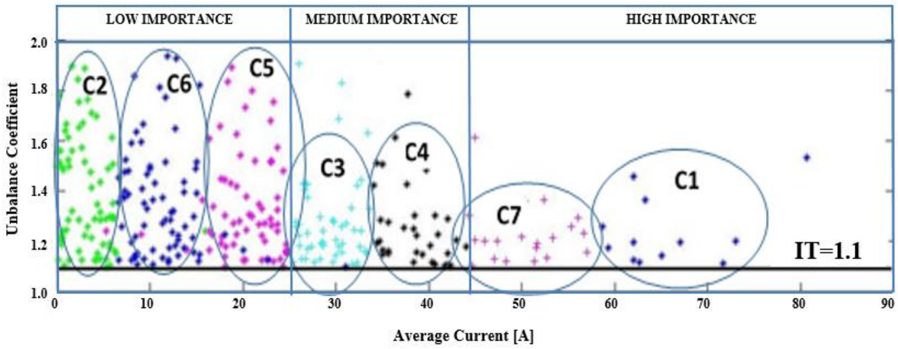

Fig. 3 – The 2-D plot of the clusters (K_{opt} = 7).

Table 1

The Statistics Indicators of the Features Associated with the Clusters

Features	**Indicators**	**Cluster**						
		C1	C2	C3	C4	C5	C6	C7
Average current [A]	Maximum value	80.67	8.00	33.67	44.00	24.90	17.00	57.00
	Minimum value	58.34	0.07	24.33	34.07	15.33	6.63	44.33
	Standard deviation	16.52	2.40	3.69	2.97	3.94	7.23	4.18
	Mean	62.27	3.15	28.91	38.27	21.07	11.94	50.29
Unbalance coefficient	Maximum value	1.53	1.86	1.91	1.95	1.95	1.97	1.61
	Minimum value	1.11	1.10	1.10	1.10	1.10	1.10	1.10
	Standard deviation	0.14	0.31	0.18	0.20	0.21	0.24	0.12
	Mean	1.24	1.45	1.27	1.28	1.34	1.38	1.23

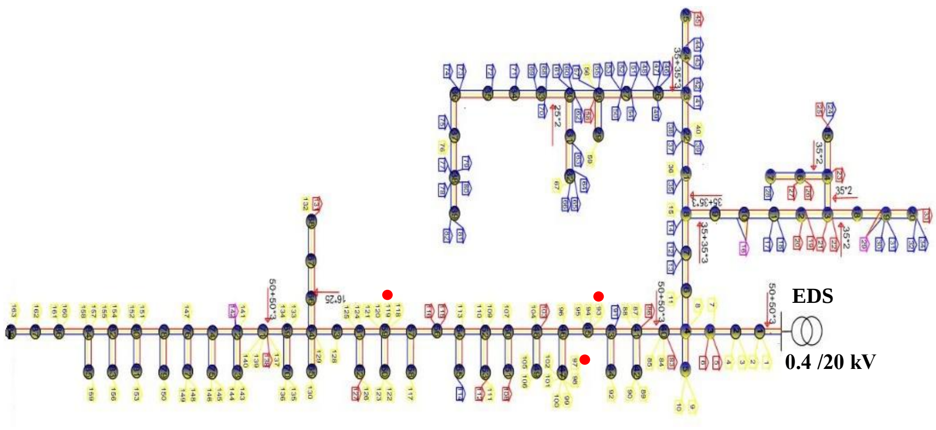

Fig. 4 – The topology of the analysed feeder with the allocation of the consumers at pillar and phase.

Based on these results, the "importance" categories have been ordered as follows C1, C7, C4, C3, C5, C6, and C2, from right to left, beginning with the highest values of the average current. This succession has been established based on the experience of the DNOs related to the obtained significant benefits (energy-savings) for the feeders with the phase currents over the value of 40A (Grigoras *et al.*, 2016). Thus, the highest importance is assigned to C1 and C7, followed by C4 and C3, and in the last positions are C6 and C2.

The efficiency of the PLB algorithm used in the second stage was demonstrated by considering a distribution feeder belonging to a *High* "importance" category (C7), having the information available for the peak load day in the CC database. This feeder was chosen due to the complete data needed in the PLB process. Of course, the algorithm will be applied for all feeders with the condition as the data on the topology and smart meter data to be accessible to the DM.

It has an average phase current of 42.6A, and the value of the unbalance coefficient is 1.26, both calculated at the peak load. Fig. 4 presents the topology of the feeder and the allocation of each consumer at the pillar. The signification of the colours is the following: red (phase *a*), yellow (phase *b*), and blue (phase *c*) for the single-phase consumers and magenta for the three-phase consumers.

From all consumers, 42 have an allocation on phase *a*, 72 on phase *b*, 47 on phase *c*, and 2 have 3-phase branching. The data provided by the meters are recorded into the database of the SMS. The characteristics of branches, referring to the cross-sections of the conductors (phase and neutral) and lengths, are presented in Table 2.

Fig. 5 presents the hourly variation of the currents in the phase and neutral conductors on the LV (0.4 kV) side of the EDS before the PLB process.

A high unbalance degree between the phase currents can be observed, the phase *b* having a higher loading than phases *a* and *c*. This operating regime of the feeder led to a current in the neutral conductor very close to phase *b*.

Table 2
The Characteristics of the Branches from the Analysed Feeder

Branch	Length [km]	Cross-section of conductor [mm^2]		Number of Phases
		Phase	Neutral	
EDS-66	1.20	50	50	3
66-68	0.08	25	16	1
64-69-88	0.84	50	50	3
5-8	0.16	50	50	3
8-25	0.20	35	35	3
23-32	0.28	35	35	3
30-39	0.28	25	25	1
8-13	0.20	35	35	3
13-20	0.12	35	35	1
13-15	0.08	35	35	1
14-17	0.08	35	35	1

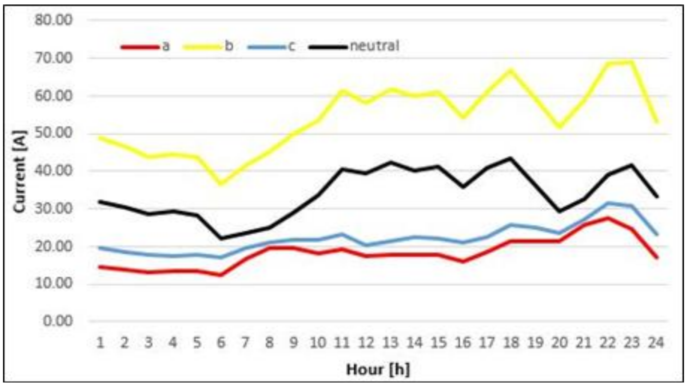

Fig. 5 – The phase and neutral currents at the EDS level (before PLB process).

The average unbalance coefficient calculated at the 0.4 kV level of the EDS is 1.26, exceeding 16% of the threshold value imposed by the DNOs. To reduce this value, the load phase balancing algorithm, presented in section 2.2, was used. The analysis of the final results highlighted that three consumers with the identification numbers (ID) 93, 97, and 119 should have the PLBD installed. Red circles mark the consumers in Fig. 4.

Figs. 6, 7, and 8 show the switching diagrams of the PLBD from each consumer. Most operations have been recorded at the consumer with ID 97 (7 phase changes), followed by the consumer with ID 93 (5 phase changes), and the consumer with ID 119 (3 phase changes).

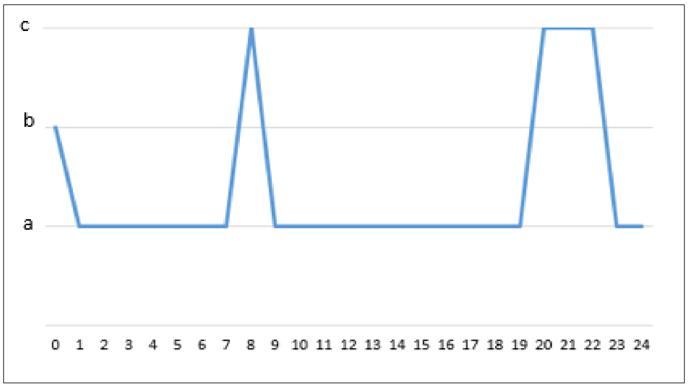

Fig. 6 – The switching diagram of the PLBD installed at the consumer ID 93.

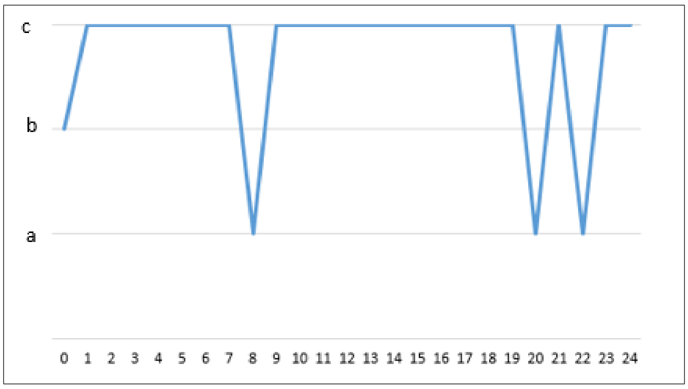

Fig. 7 – The switching diagram of the PLBD installed at the consumer ID 97.

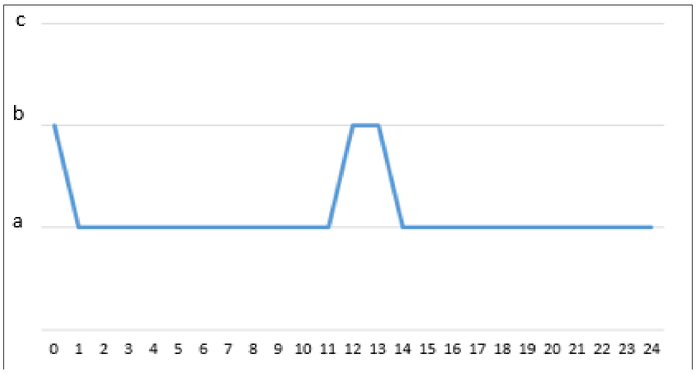

Fig. 8 – The switching diagram of the PLBD installed at the consumer ID 119.

The new hourly variation of the phase and neutral currents presented in Fig. 9 highlights the efficiency of the PLB algorithm. The value of neutral current is lower, below by 5A at each hour, and the phase currents are very close. The average unbalance coefficient decreased until 1.0021.

Figs. 10 and 11 show the hourly values of the unbalance coefficient before and after the PLB process. A significant decrease of the values was obtained, from a maximum of 1.35 at 1.0041.

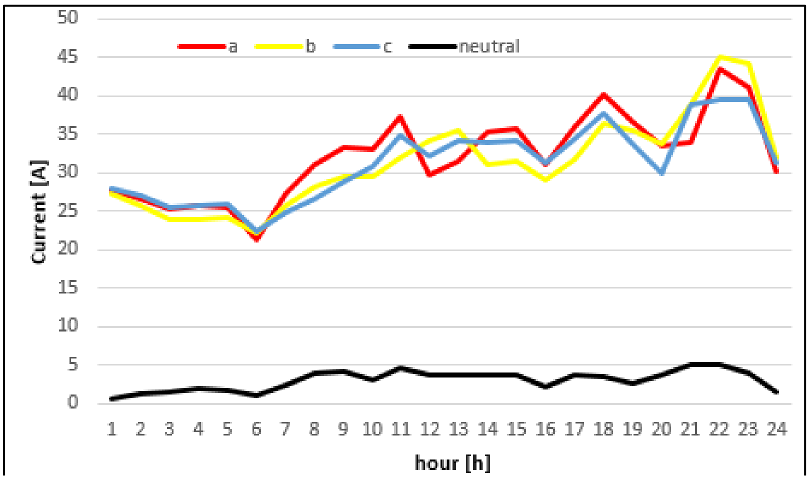

Fig. 9 – The phase and neutral currents to the 0.4 kV level of EDS (after PLB process).

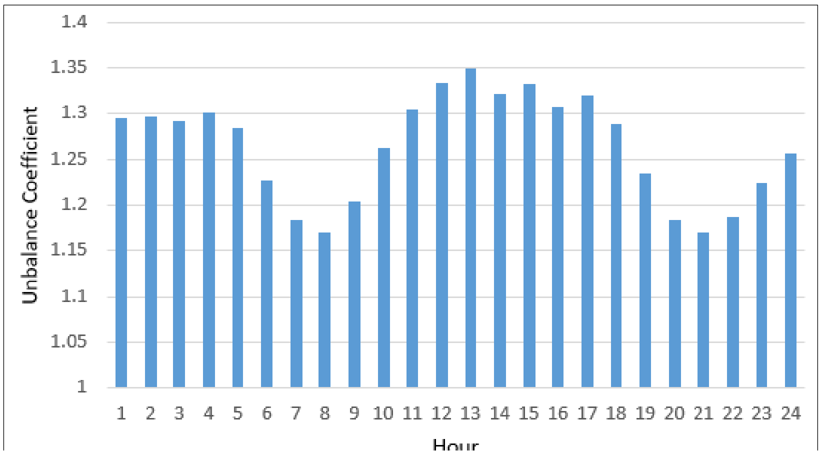

Fig. 10 – The unbalanced coefficient to the 0.4 kV level of EDS (before PLB process).

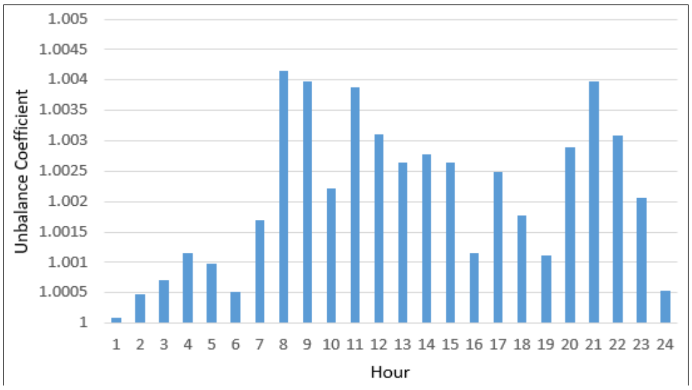

Fig. 11 – The unbalanced coefficient to the 0.4 kV level of EDS (after PLB process).

The proposed algorithm was compared in terms of the computing time and the unbalance coefficient with the proposed algorithms in the reference (Grigoras *et al.*, 2020a), where all consumers have the PLBD installed and (Grigoras *et al.*, 2020b), with a implementation degree by 17.5% (22 consumers). The second algorithm is based on a clustering-based criterion to identify the consumers with PLBD installed. It used the same computer configuration (Intel I7 and 4GB RAM) and the same programming language (MATLAB 2016). Table 3 presents the results obtained with the three algorithms, highlighting the performance of the proposed algorithm.

Table 3

The Comparison Between the Balancing Algorithms, with Various

Implementation Degree of the PLBDs [*kW*]

Studied Case	Operating Regime	Computational Time [sec]	Unbalance Coefficient	ΔW [kWh]	ΔW_S [%]
1	Unbalanced	-	1.26	34.87	-
2	Balanced: 100%	1.26	1.0017	14.10	59.56
3	Balanced: 17.5%	0.72	1.0030	14.60	58.13
4	Balanced: 2%	0.59	1.0021	19.67	43.59

The used PLB algorithm in this paper is fast (0.59 seconds versus 1.26 and 0.72 seconds,) and the average values of the unbalance coefficient at the EDS level are very close (1.0021 versus 1.0017 and 1.0030). Regarding the energy-savings, the proposed algorithm led at the smaller values with approximately 15% than the first two algorithms considering only 3 PLBDs. Although the percent of consumers equipped with the PLBDs is small, about 2%, the technical benefits are high. However, the first two solutions with 100% and 17.5% implementation of the PLBD leads at significant investments for the DNO.

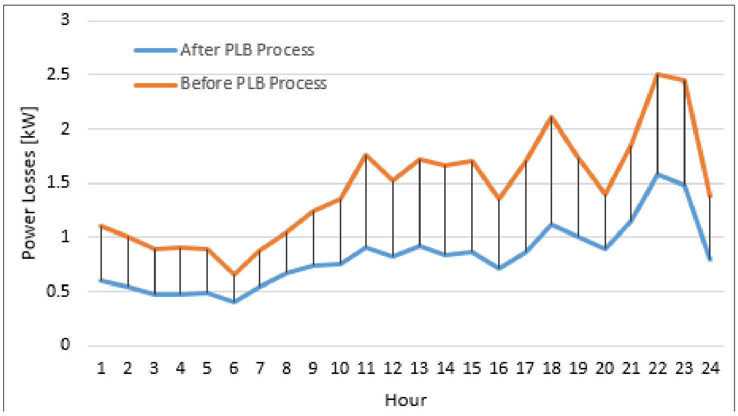

Fig. 12 – The total active power losses calculated in both analysed cases.

Table 4
The Active Power Losses Calculated Before and After PLB Process [kW]

Hour	a	b	c	Neutral	Total	a	b	c	Neutral	Total
1	0.03	0.54	0.11	0.43	1.11	0.12	0.19	0.16	0.13	0.60
2	0.03	0.49	0.10	0.39	1.01	0.12	0.17	0.15	0.11	0.54
3	0.02	0.43	0.09	0.35	0.89	0.10	0.15	0.13	0.10	0.48
4	0.02	0.44	0.09	0.35	0.91	0.11	0.14	0.13	0.10	0.48
5	0.02	0.44	0.09	0.35	0.90	0.11	0.15	0.14	0.10	0.49
6	0.02	0.31	0.08	0.25	0.66	0.07	0.13	0.11	0.09	0.40
7	0.04	0.41	0.11	0.32	0.88	0.12	0.17	0.13	0.13	0.55
8	0.05	0.50	0.12	0.38	1.05	0.16	0.20	0.15	0.16	0.67

9	0.05	0.59	0.14	0.46	1.24	0.18	0.22	0.18	0.16	0.74
10	0.04	0.66	0.13	0.52	1.36	0.18	0.22	0.19	0.16	0.75
11	0.05	0.87	0.15	0.68	1.76	0.23	0.26	0.24	0.18	0.91
12	0.04	0.77	0.12	0.60	1.53	0.13	0.31	0.20	0.19	0.83
13	0.04	0.86	0.13	0.68	1.72	0.15	0.34	0.23	0.20	0.92
14	0.04	0.82	0.14	0.65	1.66	0.20	0.24	0.23	0.17	0.84
15	0.04	0.85	0.14	0.67	1.70	0.21	0.25	0.23	0.17	0.86
16	0.04	0.67	0.13	0.53	1.36	0.16	0.21	0.20	0.15	0.71
17	0.05	0.85	0.15	0.67	1.71	0.21	0.26	0.23	0.17	0.87
18	0.06	1.04	0.19	0.82	2.11	0.26	0.34	0.29	0.23	1.12
19	0.06	0.84	0.18	0.66	1.74	0.22	0.32	0.24	0.23	1.01
20	0.06	0.66	0.16	0.51	1.40	0.19	0.29	0.20	0.21	0.89
21	0.09	0.87	0.21	0.68	1.84	0.19	0.39	0.31	0.26	1.15
22	0.10	1.18	0.29	0.93	2.50	0.32	0.53	0.35	0.39	1.58
23	0.08	1.17	0.27	0.93	2.45	0.28	0.50	0.35	0.35	1.48
24	0.04	0.66	0.15	0.53	1.38	0.15	0.26	0.21	0.18	0.80

Fig. 12 shows a comparison between the total active power losses obtained in both cases, and Table 4 contains details on the losses in the phase and neutral conductors calculated at each hour from the analysed period (1 day) in both cases (before and after the PLB process).

The maximum value of the difference is recorded at hour 18 (0.99 kW), the minimum value at hour 6 (0.26 kW), and the average value is 0.63 kW.

The effects on the energy losses are positive, leading to energy-savings, δΔW, by 15.2 kWh, representing 43.6% from the initial energy losses, see Fig. 13.

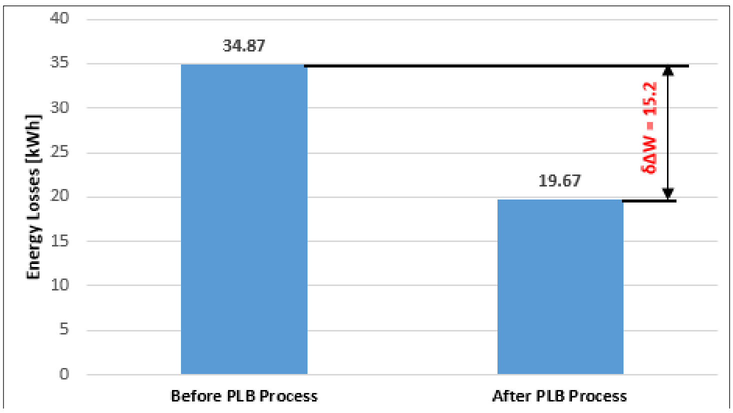

Fig. 13 – The total active energy losses calculated in both analysed cases.

4. Conclusions

The fight against climate change is one of the five main topics of the Europe 2030 strategy for smart, sustainable, and inclusive growth. The specific objectives of this strategy aim to ensure that, by 2030, the following levels are achieved compared to the year 1990 levels: the greenhouse gas emissions are reduced by 40% compared to the year 1990 levels, improving the energy efficiency by at least 32.5%, and obtaining at least 32% of the total energy from renewable sources. Regarding the increase of energy efficiency, the EU Directive on this direction encourages the DNOs to reduce the energy losses, implement a coherent investment program, and take due account of energy efficiency and network flexibility. In Romania, the phase load balancing is found among the main measures to improve the energy efficiency reported by the Romanian DNOs at the Energy Regulation Authority.

Considering this measure, a clustering-based methodology to identify the LV feeders with high unbalance degrees has been proposed. In the first stage, for the classification of the feeders into "importance" categories (*High*, *Medium*, and *Low*) depending on the unbalanced coefficient, calculated at the 0.4 kV level of the EDS, and the average current in the peak load period used the clustering techniques. The classification took into account the maximum technical benefits which could be obtained for each feeder. In the second stage, a PLB algorithm is applied for each feeder from the "importance" categories to identify the minimum number of consumers that will have installed PLBD. The methodology can have a limitation in some cases. It refers to the impossibility of applying the PLB algorithm for the networks with incomplete or missing data (uncertain topology, the connection of consumers by phases, or the non-inclusion of all in the smart metering system).

Testing the methodology was done considering a CM database containing the phase and neutral currents measured at the peak load period for 628 feeders. Seven clusters divided into the three "importance" categories have been obtained using the K-means clustering algorithm. A feeder with a *High* importance for the balancing strategy, having all consumers integrated into SMS, has been chosen to demonstrate the efficiency of the PLB algorithm from the second stage. The results highlighted that its application could lead to low investments to ensure an unbalance coefficient below the agreed value by the DNO (1.1). The PLBDs will be only installed to 3 consumers, meaning 2% from all consumers, and can save significant energy amount (43.6%, in the analysed period).

The future work will integrate into the PLB algorithm the electric distances between each consumer to the EDS and the weight of demands in the unbalance coefficient to lead to increased technical benefits.

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METODOLOGIE BAZATĂ PE TEHNICI DE CLUSTERING PENTRU ECHILIBRAREA ÎNCĂRCĂRII FAZELOR ÎN REȚELELE ELECTRICE DE DISTRIBUȚIE DE JOASĂ TENSIUNE

(Rezumat)

Ținând cont de importanța creșterii eficienței energetice în rețelele electrice de distribuție, în cadrul lucrării se propune o metodologie de echilibrare a încărcării fazelor, care are la bază identificarea distribuitorilor de joasă tensiune caracterizați de un grad de dezechilibru ridicat. În prima etapă, distribuitorii de joasă tensiune sunt clasificați în categorii de importanță (*High*, *Medium* și *Low*) folosind algoritmul K-Medii, utilizând ca date de intrare coeficientul de dezechilibru şi curentul total injectat înregistrat în perioada vârfului de sarcină. Aceste categorii vor conduce la stabilirea ierarhiei distribuitorilor incluşi în procesul de echilibrare. În a doua etapă, pentru fiecare distribuitor, în ordinea stabilită în prima etapă, se determină mulțimea consumatorilor la care va fi montat un dispozitiv cu rolul de a comutare de pe o fază pe alta consumatorul în funcție de soluția identificată de un algoritm de echilibrare la nivel de post de transformare. O bază de date care conține valorile curenților în conductoarele de fază și neutru măsurate în perioada vârfului de sarcină pentru 628 distribuitori a fost folosită în prima etapă pentru obținerea categoriilor de importanță. În a doua etapă, a fost ales un distribuitor cu importanță *High* pentru demonstrarea eficienței algoritmului de echilibrare propus. Deși mulțimea de consumatori la care vor fi montate dispozitivele de comutare are doar 3 consumatori (aproximativ 2% din totalul de 163 de consumatori), beneficiile tehnice obținute sunt mari, cuantificate printr-o economie de energie în perioada analizată (1 zi) de 43,6%.