Chapter

The Optimal Operation of Active Distribution Networks with Smart Systems

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Abstract

The majority of the existing electricity distribution systems are one-way networks, without self-healing, monitoring and diagnostic capabilities, which are essential to meet demand growth and the new security challenges facing us today. Given the significant growth and penetration of renewable sources and other forms of distributed generation, these networks became "active," with an increased pressure to cope with new system stability (voltage, transient and dynamic), power quality and network-operational challenges. For a better supervising and control of these active distribution networks, the emergence of Smart Metering (SM) systems can be considered a quiet revolution that is already underway in many countries around the world. With the aid of SM systems, distribution network operators can get accurate online information regarding electricity consumption and generation from renewable sources, which allows them to take the required technical measures to operate with higher energy efficiency and to establish a better investments plan. In this chapter, a special attention is given to the management of databases built with the help of information provided by Smart Meters from consumers and producers and used to optimize the operation of active distribution networks.

Keywords: smart metering, active distribution networks, optimal operation, load balancing, demand response, voltage control

1. Introduction

At present, at European level, distribution networks have a high degree of automation of distribution, using industrial standards, so transition from the current situation to the active distribution networks is technically feasible. The concepts of active distribution networks (ADN) defined both in the industrial and academic environments take different forms by focusing attention on several particular issues of concern: active consumers, distributed generation, active participation in the electricity market, etc. Each of these development directions is designed to respond to a part of issues regarding the ADN, similar to the pieces of a puzzle game. It is obvious that the ultimate success of any initiative, which refers at the transition to the ADN, is determined by the presence of the smart entity that consistently places the pieces of the game in a consistent and consistent manner [1].

It is important to address the general architecture of a control system to implement and integrate new solutions in the ADN (**Figure 1**).

To facilitate the transmission of information between new smart systems and actual distribution management systems, an integrative middleware system should be devised. The flexibility of the ADN and smart monitoring and control components is still a very important issue to be addressed. By using open standards, the ADN is designed to be expanded with virtually any future functionality [1]. Data provided by the smart meters allows detailed analyses on the operation of networks, giving a strategic advantage to distribution system operators (DSOs) in identifying the network zones or distributions which have a performance below acceptable quality, maximizing the impact of profitable investments (such as maintenance works, investments in new equipment and innovative technologies, replacing sub- or over-sized distribution transformers from the MV/LV electric substations). Also, it should be noted that these smart meters can allowed the protection of electric installations from the consumers at overvoltages, reducing the problems in case of possible incidents in the electricity grid. A meter that actively communicates with a central system can provide the important information about the position, type and magnitude of possible incidents from the network, reducing the time for intervention staff and discomfort for customers as some interventions can be made remotely [2]. The smart meters are integrated into a computerized application (smart metering system) so they can be managed centrally and remotely (**Figure 2**). In the ADN the benefits are win-win between the actors (DSO, consumers and energy producers from the renewable sources integrated into the network).

The issues such as the real-time update of consumer data on smart grids, or the integration of energy storage solutions (a critical issue in the case of discontinuous renewable energy) could be addressed by DSOs. It is estimated that ADN, summing up and extrapolating the individualized flexibility of smart meters, will be more versatile in monitoring power flows and adapting dynamically to energy consumption, helping the load balancing on the phases. The bidirectional communication is

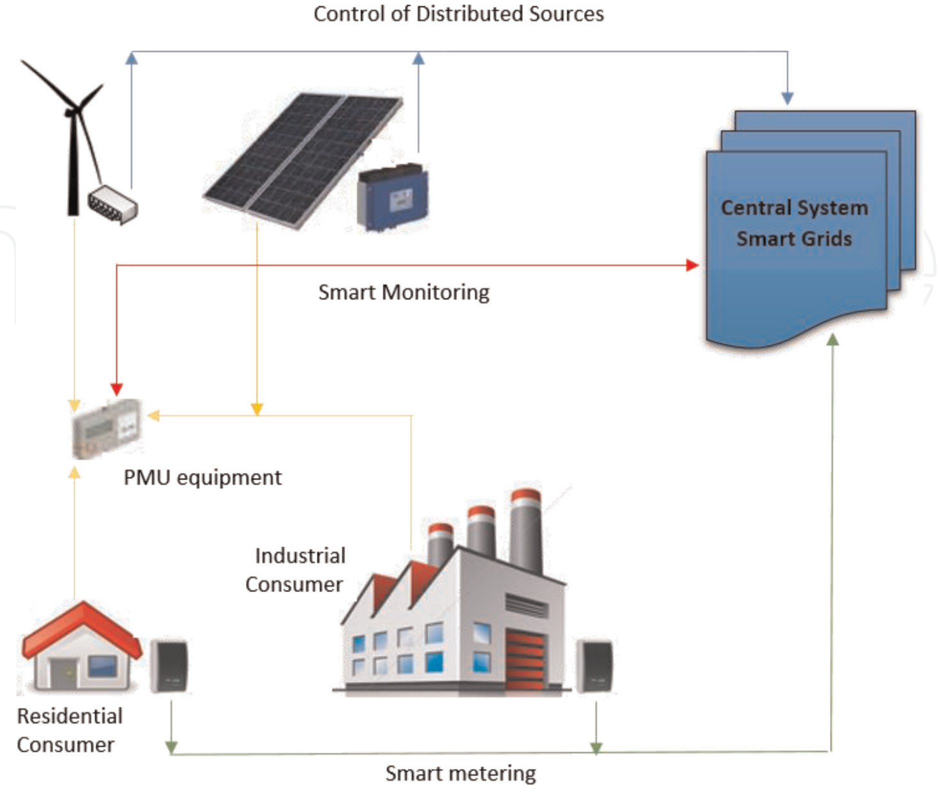

Figure 1.
The general architecture of a control system in active distribution networks [1].

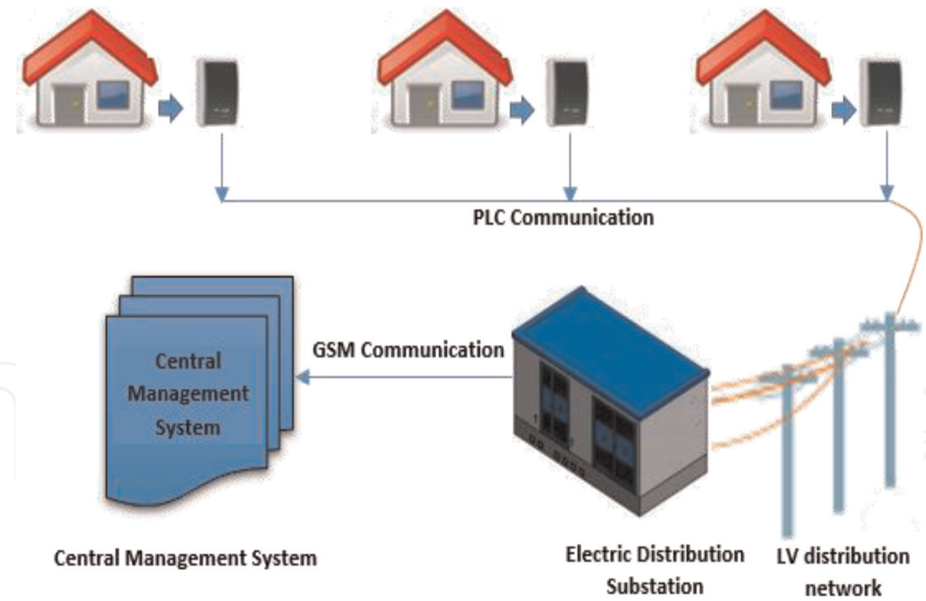

Figure 2.
The communication between the smart metering and management systems.

possible between central system from the DSO and smart meters. Also, the growing ability to integrate "green" generating unit into the network could be complemented with meteorological forecasting functions, and estimations regarding the variation in photovoltaic and wind energies could be correlated, at central level, with the daily forecasting of consumption or distributed energy (correlating with market trends through day-ahead market indicators) [3].

The current shift from fossil/nuclear to large-scale renewable energy sources (RES) brings new challenges in grid operation. The unpredictability of wind farm generation must be alleviated by DSOs with a higher flexibility of traditional generation sources and improved congestion management algorithms [4]. Also, with the increasing penetration of small distributed energy generation sources in the residential sector, the traditional consumers become prosumers, entities who generate electricity locally for their own use, and want to sell the excess power on the market [5]. For enabling the access of prosumers in the market, regulators, DSOs need to work together to create the technical infrastructure, trading regulations and management procedures for Distributed Generation (DG) sources and Demand Side Management (DSM) [6]. Inside the DSM paradigm, Demand Response (DR) is a tool that can be used by DSOs for improving system security and supply quality when operating at peak load or under restrictions imposed by the presence of RES. DR focuses on load reduction for short time intervals (e.g., hours) at consumer sites, by voluntary or automated disconnection of significant loads. To engage in DR programs, consumers or prosumers need to be equipped with Smart Metering infrastructures and Energy Management Systems (EMS), capable of automatically managing the demand and generation at household or microgrid level.

DR initiatives are currently applied for industrial consumers, which can reschedule their technological processes by shifting the operation of high-demand loads away from peak load hours. In the residential sector, DR implementation is in an incipient stage, due to consumer unawareness or lack of interest, high cost of infrastructure at the consumer side or lack of regulations or market framework [7]. One key factor for enabling the development of residential DR is the emergence of aggregators, local DSOs or independent players, which can cumulate the load reduction from several small consumers or prosumers and manage entire LV/MV network areas for DR as single entities [8]. For this purpose, aggregators can use optimization algorithms which distribute the load disconnected because of DR in a way that the technical parameters of the distribution network, such as active power losses, phase loading or bus voltage level, are kept in acceptable intervals or improved.

Voltage level control is an essential process in secure and efficient active distribution network (ADN) operation [9]. The ADN were built one century ago and they have been renewed for decades to respond to changes of end-user needs. The electricity is produced in classical grids by the central power plants, transmitted and delivered through ADN to the end-user in a one-way direction [10]. LV ADN s supply a large number of one-phase consumers, connected in a three-phase grid. Because the number of consumers and their load behavior presents a continuously dynamic, the load pattern of the three phases of the grid is different. One of the cheapest measures that a DSO can take is to optimize the steady state through voltage control and power losses and voltage drop minimization. Thereby, the real operation state of an ADN is unbalanced, and in this type of grid, the voltage control represents a relevant index, especially for LV grids, which are frequently built using OHLs mounted on poles, with supply paths extending more than 1–2 km in length. The remainder of this chapter is organized as follows. Section 2 treats the phase load balancing problem in ADN. Section 3 presents a new approach for Demand Response in ADN, and Section 4 proposes a simple method for voltage control in the real AND. For all proposed approaches, their implementation and the obtained results are discussed.

2. Phase load balancing in active distribution networks

2.1 Smart devices in phase load balancing

In the active distribution networks to operate in balancing symmetric regime, the currents on the three phases should have equal values. But, due to the unequal distribution of the consumers amongst the three phases along with variations in their individual demand appear the unequal loading of phases the so-called “current unbalance” [9]. In this context, the DSOs should take the measures by installing, besides the smart meter, a device that allows switching from phase to phase in order to balance the phases. This measure should lead at the minimization of active power losses, which represents the cheapest resource of DSOs in order to improve the energy efficiency of distribution networks [10]. In [11] is presented a constructive variant for a digital microprocessor-based device. The principle is easy, namely, for this device, a trigger module based on the minimum and maximum voltage thresholds is set so that the load to switch from the service phase to other if these thresholds are violated. The principle structure is presented in **Figure 3**.

The device is connected to the four-wire three-phase network (see **Figure 3**) through inputs 1–4 at the phases a, b, c, and the neutral (N). If it is assumed that the phase a is initial connected phase of the consumer, the voltage in this phase is monitored to be within the thresholds set. Also, the presence and voltage value of on the other two phases phase is monitored and if the voltage value on phase a fall outside the thresholds, the device will switch quickly on the phase with the higher value of voltage, but inside of thresholds (a switching delay is not more than 0.2 s) [11]. The switching process has the following succession from the phase a to b, from b to c. In [12] is presented another structure of a three-phase unbalanced automatic regulating system whose operation principle is based on the real-time monitoring and processing of three-phase current that is measured with the help of an external current transformer. A smart module equipped with a microprocessor will determine if the distribution network has a load unbalance on the three phases, then will

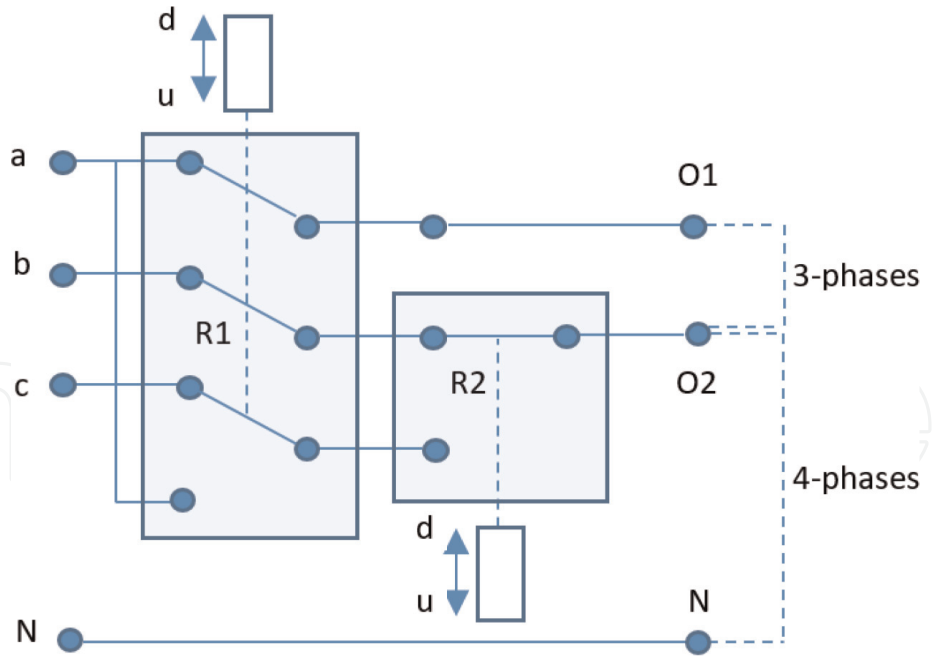

Figure 3.
The structure of digital balancing system.

determine which will be the new allocation of the consumers on phases such that the unbalance degree to be minimum. This objective can be obtained if the consumers with the higher values of the absorbed current are switched on the phase with a smaller current. At the consumers, the switch unit has in its structure a thyristor and magnetic latching relay. The role of thyristor is cut off by zero switching at the moment of input and removal, and the magnetic latching relay is switched on. The main advantages of thyristor are represented by inrush characteristic and short conduction time, because they do not lead to the generation of heat. Magnetic relay has no impact on distribution network, and it is an ideal three-phase unbalance control switch. The structure of three phase unbalance automatic regulation system is presented in **Figure 4**. The data concentrator gives the commutation command at those switch units which must transfer the consumer to the current phase on a specified phase such that to ensure as low as possible unbalance degree at the level of network.

Another structure of a smart device to connect a consumer at the distribution network is presented in [13], see **Figure 5**. According to the proposed structure, the

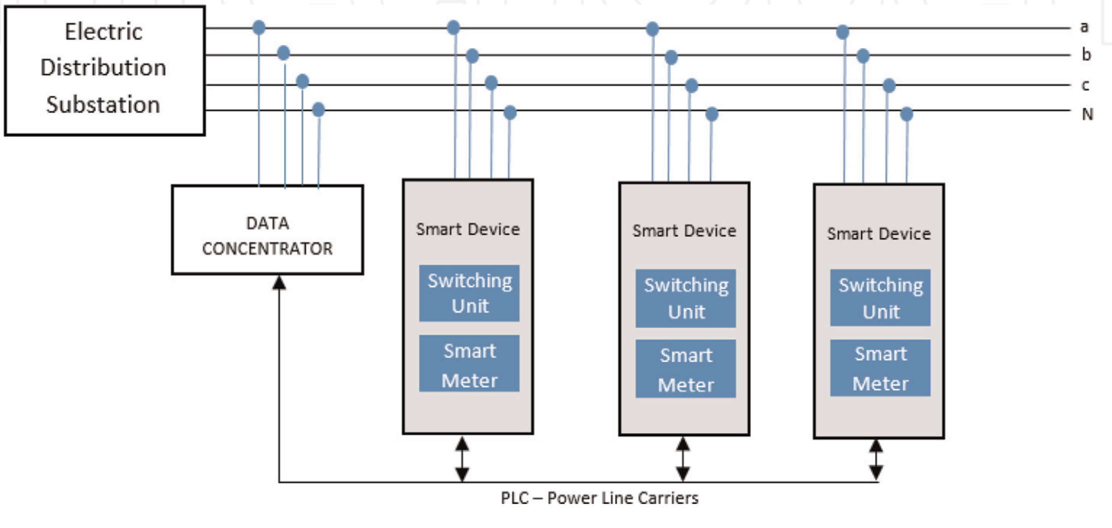

Figure 4.
The structure of smart phase microprocessor-based device.

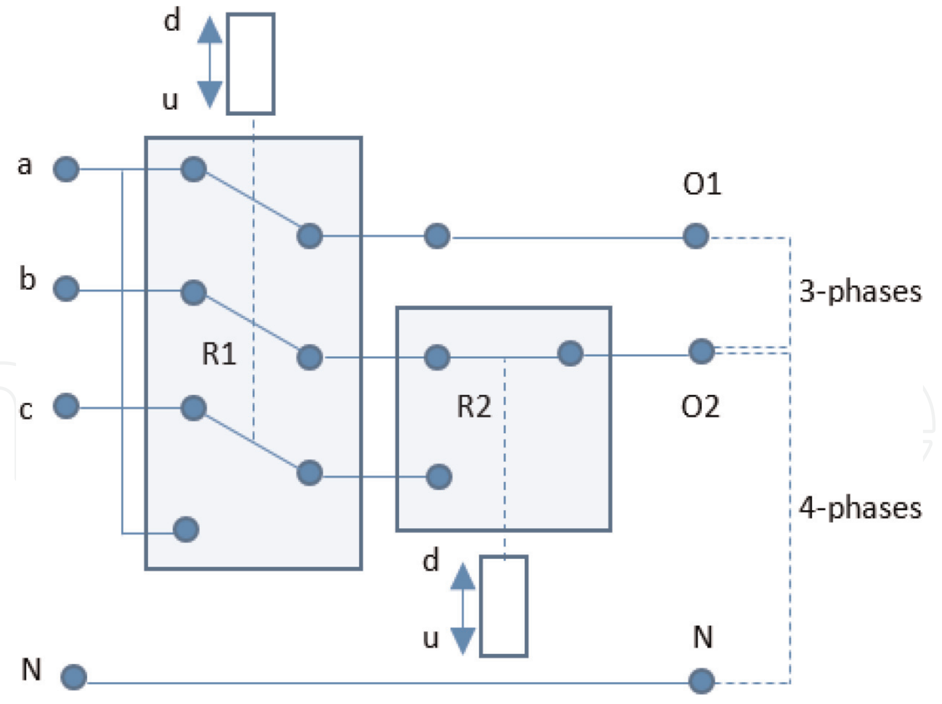

Figure 5.
The smart structure with the phase selector, [6].

Relays	R1		R2		Outputs		230 V output	
Position	**d**	**u**	**d**	**u**	**O1**	**O2**	**3-phase**	**4-phase**
1	X		X		a	b	a-b	b-N
2	X			X	a	c	a-c	c-N
3		X	X		b	c	b-c	c-N
4		X		X	b	a	b-a	a-N

Table 1.
The logic of phase selection.

smart meter is provided with a phase selector by means of which the outputs can be switched from one phase to another. In this way, when there are many 1-phase consumers connected to the distribution network, the DSO can remotely control the phase selectors in order to allocate the load over the different phases such that the unbalance degree to be minimum. In this way, a more even spreading of the load on the three phases of the distribution network can be achieved, see **Table 1** where is presented the logic of phase selection. 3-phases the output is connected to O1 and O2, respectively in the case 4-phases the output is connected to O2 and O2 The device send at the central system information about the power consumption and state (ON/OFF), which can send back the parameters for establishing the phase switching operations, after the scheme presented in **Figure 5**. Depending on the type of devices and the choice communication support, the DSOs can obtain a reliable structure, which can make the transition toward the active distribution networks.

2.2 The smart metering-based algorithm

In this paragraph, an algorithm to solve the phase load balancing (PLB) problem using a heuristic approach is proposed. This is applied to find the optimal connection phase of the 1-phase consumers such that the unbalance degree at the level of each pole to be minimum. The algorithm is based on knowing the topology of active distribution network when it will be implemented. The input data are referred at the number of poles (connection points), connected phase of each consumer, the pole when is connected the consumer, the type of consumer (1-phase or 3-phases) and load profiles provided by the smart meters. If the smart meter cannot communicate with the central unit then the algorithm will typical profiles associated to consumers without smart meters, based on the energy consumption categories and day type (weekend and working), knowing the daily energy indexes. The objective is finding the optimal phase connection for all consumers using the expression of current unbalance factor (CUF). Ideally, the value of this factor should be 1.00. But these values are very difficult to be obtained from the technical reasons and by the dynamic of loads. Thus, in most cases the obtained values will close to 1.00. The CUF factor could be evaluated using the following equation [9, 10], and the value should be under 1.10 p.u:

$$CUF_h^{(p)} = \frac{1}{3}\left[\left(\frac{I_{a,h}^{(p)}}{\bar{I}_{(a,b,c),h}^{(p)}}\right)^2 + \left(\frac{I_{b,h}^{(p)}}{\bar{I}_{(a,b,c),h}^{(p)}}\right)^2 + \left(\frac{I_{c,h}^{(p)}}{\bar{I}_{(a,b,c),h}^{(p)}}\right)^2\right] \quad p = 1, \dots, N_p, \quad h = 1, \dots, T \tag{1}$$

$$\bar{I}_{(a,b,c),h}^{(p)} = \frac{1}{3}\left(I_{a,h}^{(p)} + I_{b,h}^{(p)} + I_{c,h}^{(p)}\right) \quad p = 1, \dots, N_p, \quad h = 1, \dots, T \tag{2}$$

$$I_{a,h}^{(p)} = \sum_{k=1}^{Nc_a^{(p)}} i_{a,k,h}^{(p)}; \quad I_{b,h}^{(p)} = \sum_{k=1}^{Nc_b^{(p)}} i_{b,k,h}^{(p)}; \quad I_{c,h}^{(p)} = \sum_{k=1}^{Nc_c^{(p)}} i_{c,k,h}^{(p)} \quad p = 1, \dots, N_p, \quad h = 1, \dots, T \tag{3}$$

$$Nc^{(p)} = Nc^a{}_{(p)} + Nc^b{}_{(p)} + Nc_c^{(p)} \quad p = 1, \dots, N_p \tag{4}$$

where: a, b, and c indicate the three phases of network; $\bar{I}^{(p)}{}_{(a,b,c),h}$—the average phase current at the pole p and hour h; $I^{(p)}{}_{a,h}$, $I^{(p)}{}_{b,h}$, $I^{(p)}{}_{c,h}$—the total currents of phases a, b and c at pole p and hour h; $i^{(p)}{}_{a,k,h}$—the current of consumer k connected on the phase a, at the pole p and hour h; $i^{(p)}{}_{b,l,h}$—the current of consumer l connected on the phase b, at the pole p and hour h; $i^{(p)}{}_{c,m,h}$—the current of consumer m connected on the phase c, at the pole p and hour h; $Nc^{(p)}{}_a$, $Nc^{(p)}{}_a$, and $Nc^{(p)}{}_a$—the number of consumers connected on the phases a, b, and c, at the pole p; $Nc^{(p)}$—the total number of consumers connected at the pole p; N_p—the number of poles from the network; T—analysed period (24 h for a day or 169 h for a week).

The proposed algorithm has as start point the final poles and tries to balance the load on each phase at all poles until at the LV bus of the supply electric substation. The dynamics of unbalance process is represented by the switching from a phase on one from the other two phases (for example, from phase a to phases b or c) of some consumers such that the factor CUF to have a minimum value at the level of each pole and hour. In **Table 1**, all possible combinations in two distinct cases (3-phases and 1-phase) are presented.

Starting from the last pole N_p, depending on the initial connection of the consumers, the factor CUF could have values between 1 and 2. The minimum value, equal with 1, can be obtained in the ideal case (perfectly balanced), when the sum of phase currents corresponding the consumers are identical, and the maximum value 2 corresponds to the maximum unbalancing when only one phase current has a high value while the other two the phase currents have the values equal with 0 or close to 0. Finally, for the factor *CUF* on the LV side of the electric distribution substation (link with external grid) it is obtained the minimum value, very close to 1.0.

The minimization of the deviation between phase currents, at the level of each connection pole p (p = 1, …, N_p) at each hour h, represents the objective of the balancing problem, [7, 8]:

$$\min(\varepsilon) = \min\left(CUF_h^{(p)}\right) \quad p = 1, \ldots, N_p, \quad h = 1, \ldots, T \tag{5}$$

The problem is solved with the combinatorial optimization. Generally, a combinatorial problem is solved by total or partial enumeration of the set of its solutions (noted with Ω) [10]. In the Total Enumeration method, finding the optimal allocation $x^* \in A$, where A is the set of admissible solutions, requires the generation of all possible combinations of values given to the variables, for all elements from the set Ω, see **Table 2**. The partial enumeration approach is characterized by finding the optimal solution x^* by generating the some part from the Ω and adopting the assumption that in the remained part does not contain the optimal solutions. Regardless of the enumeration scheme, once an element $x \in \Omega$ is generated, the following two steps are performed: (1) It is investigated if element $x \in A$; if NO another element in Ω is generated. If YES, go to the next step; (2) Compare the current value of the objective function with the obtained value for the best element found in step 1; if the value of the objective function is improved (in the optimal sense), x is retained as the best item found in the set A.

Otherwise, x is dropped and a new element of Ω is generated. It is very important to highlight that the generation of the set Ω or even a part of this set does not mean the memorization of the generated elements for two reasons: there are many and then unnecessary (except the best element found in a certain iteration of the enumeration). The flow chart of the proposed algorithm is given in **Figure 6**.

To be implemented in the active distribution networks, a system with the structure presented in **Figure 4** should be used. The system contains the smart equipment installed at the consumers consisting two components and the data concentrator with an attached software infrastructure which integrate the proposed algorithm. The communication between smart equipment and data concentrator could be ensured by Power Line Carriers (PLC). From the consumers the transferred data refer at the absorbed load (current or active/reactive powers) and the connection phase. The data concentrator will transmit to each consumer the new connection phase.

2.3 Case study

The proposed method has been tested on a real distribution network from a rural area, see **Figure 7**. The main characteristics of network (poles, total length, cable type, cable section, sections length, number, type (single/three phase) and connection are indicated in **Table 3**. The connection phase of each consumer reflects the

Phases	Initial allocation	Final allocation
3-phases	[a ǀ b ǀ c]	[c ǀ a ǀ b] or [b ǀ c ǀ a] or [a ǀ b ǀ c]
1-phase	[a ǀ ○ ǀ ○]	[○ ǀ a ǀ ○] or [○ ǀ ○ ǀ a] or [a ǀ ○ ǀ ○]
	[b ǀ ○ ǀ ○]	[○ ǀ b ǀ ○] or [○ ǀ ○ ǀ b] or [b ǀ ○ ǀ ○]
	[c ǀ ○ ǀ ○]	[○ ǀ c ǀ ○] or [○ ǀ ○ ǀ c] or [c ǀ ○ ǀ ○]

Table 2.
Phase switching combinations for CUF minimization.

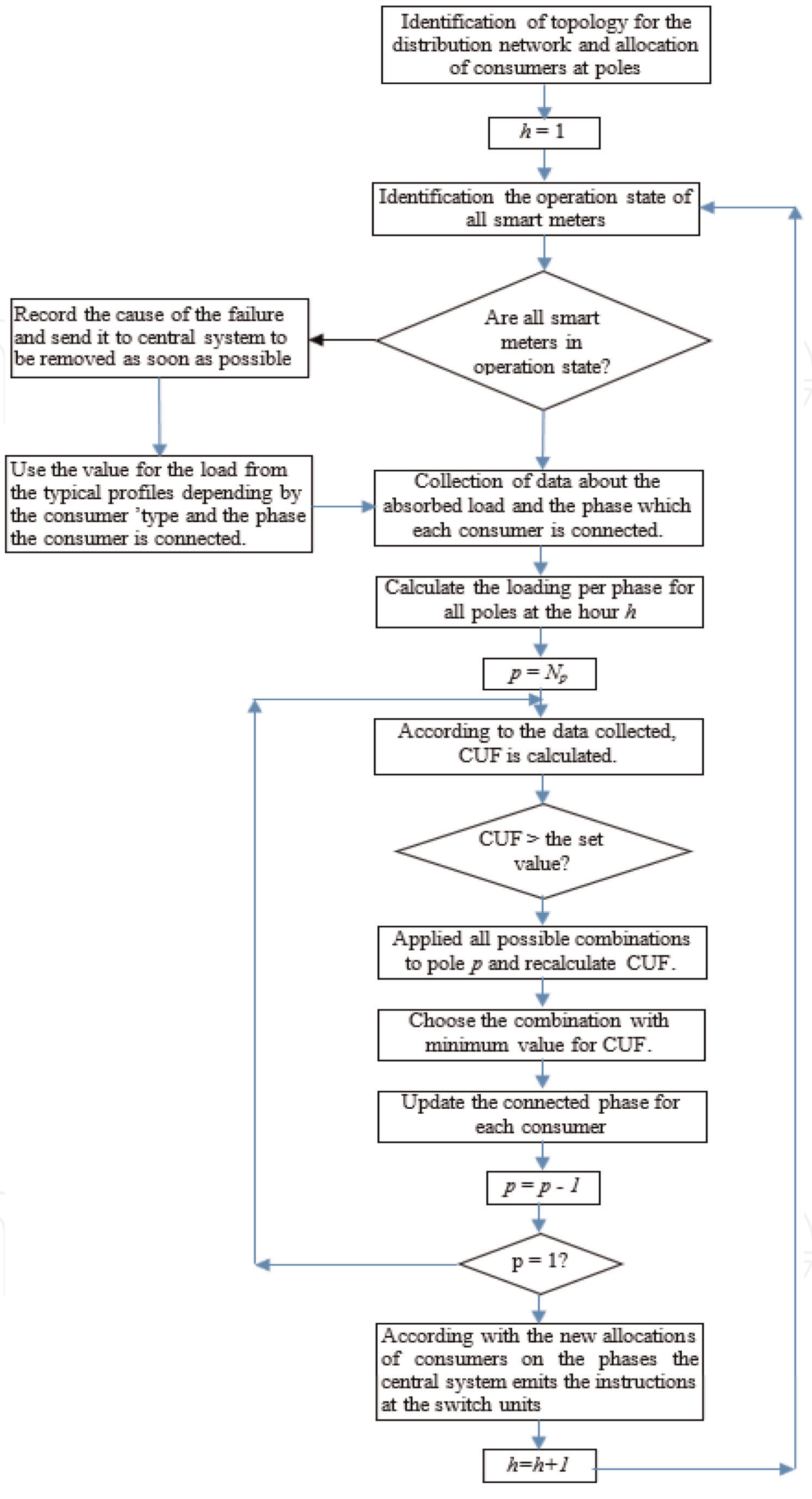

Figure 6.
The flow-chart of proposed algorithm.

situation real identified through visual inspection. The load profiles for each consumer integrated into the Smart Metering system were imported for the analysis period (27December 2017–2 January 2018). The loadings on each phase at the pole level, starting with the last pole and reaching at LV side of the electric substation, were calculated. The power flows on the three phases over the 24 h time interval on

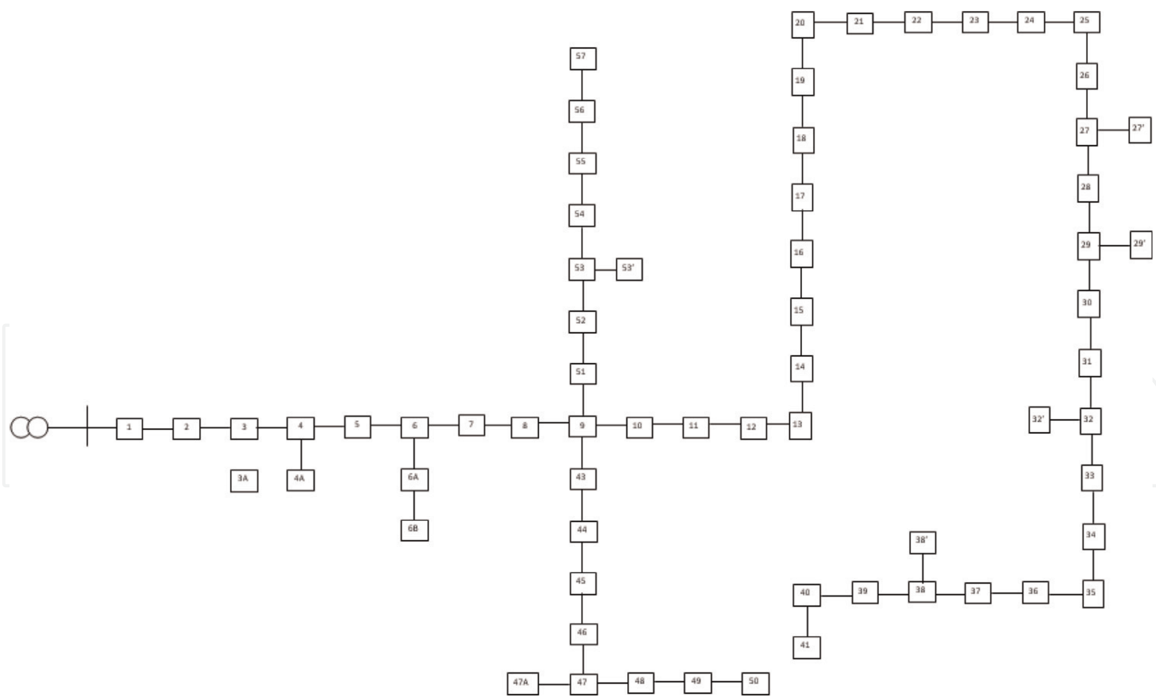

Figure 7.
The topology of test LV active distribution network.

Number of poles	Total length [m]	Data about consumers				Data about conductors		
		R	S	T	Three-phases	Type	Section [mm^2]	Length [m]
67	2560	33	28	17	6	Classical	3×35 + 35	720
		84					3×50 + 50	1840

Table 3.
The main characteristic for the analyzed feeder.

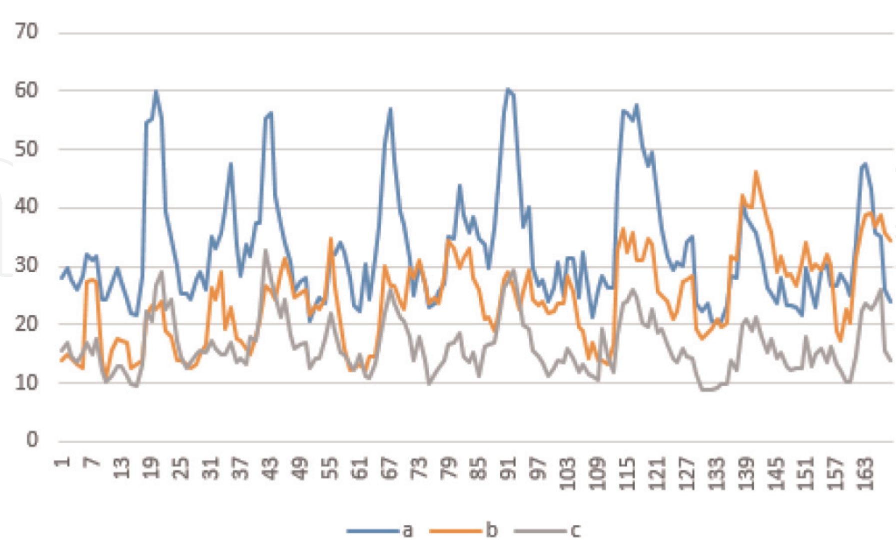

Figure 8.
The phase loading—section 0-1 [A] (initial situation—unbalanced case).

the first section are shown in **Figure 8**. It can be observed a high current unbalance degree. This degree was evaluated using the CUF factor calculated with Eq. (1).

The average value of CUF in the unbalancing case is 1.12, above the maximum admissible value (1.10). Using the proposed method, the obtained currents had the

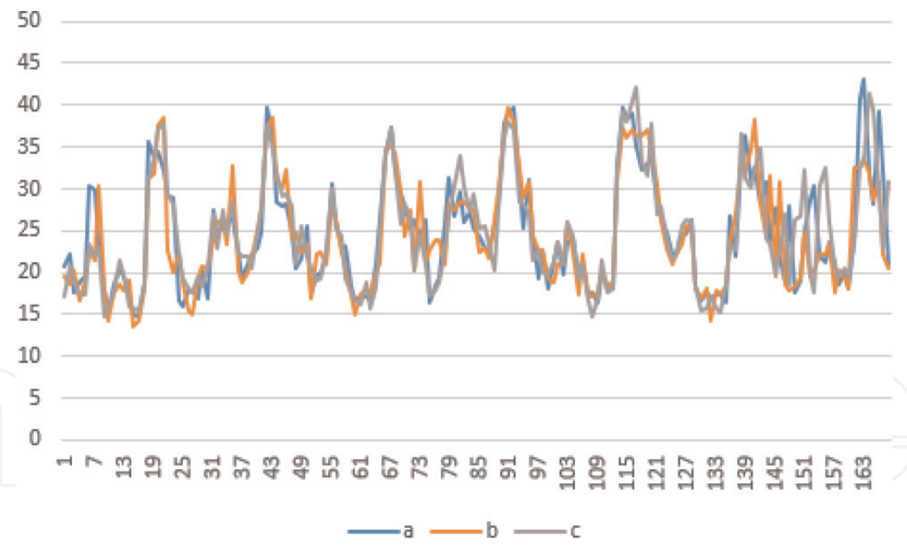

Figure 9.
The phase loading—section 0-1 [A] (final situation—unbalanced case).

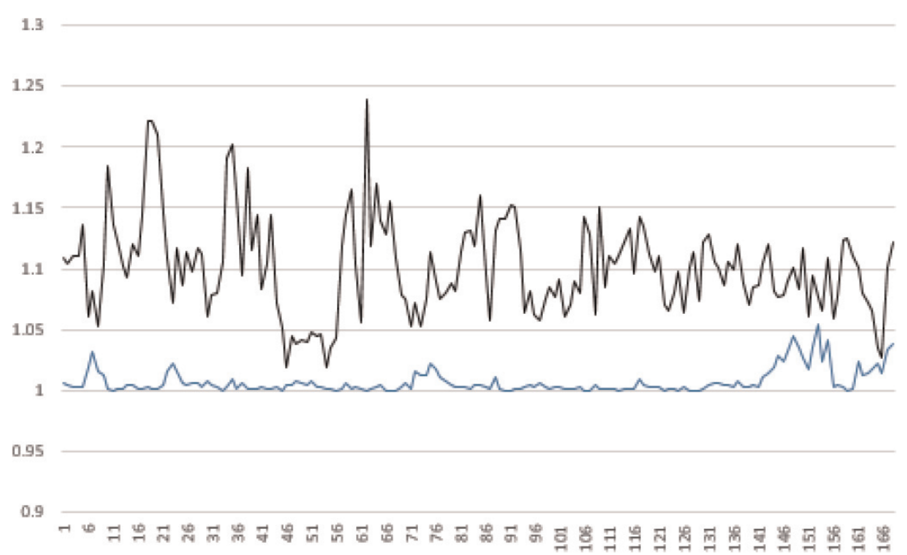

Figure 10.
Variation of CUF factor, pole no. 1.

very close values were obtained on the three phases, as can be seen in **Figure 9**, and the CUF factor was reduced to the value by 1.007. The variation of the CUF factor in the analyzed period for both situations is presented in **Figure 10**. Because the phase current unbalancing leads to voltage unbalancing, **Figures 11** and **12** show the phase voltage variation at the pole level in the study period. These values were obtained from the steady state calculation for each hour, in both situations (unbalanced and balanced) (**Figure 13**).

It can be observed that in the unbalanced case the minimum value of voltage is recorded at the pole no. 41, identified by the red color in the scheme, on the phase b ($U_b(41)$ = 221.8 V). Following the application of the balancing algorithm, the values of voltage on the phases of the network is approximately equal, and at the pole no. 41 41, on phase *b*, it was recorded an improved value $U_b(41)$ = 227.4 V, very close to the rated value (230 V). Also, the energy losses were reduced from 92.70 to 68.38kWh (by 26.23%), **Table 4**. A comparison between the energy losses on the phase and the neutral conductor in the both cases (unbalanced and balanced) is

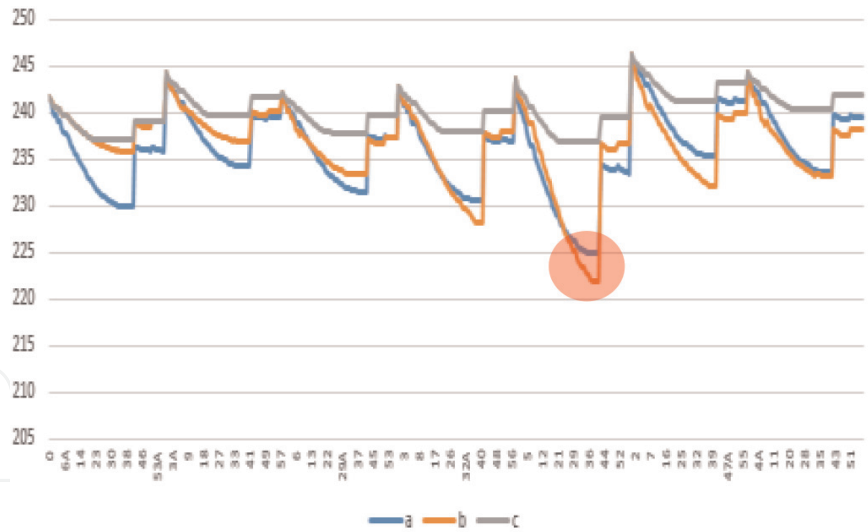

Figure 11.
Voltage variation in the nodes [V] (initial situation—unbalanced case).

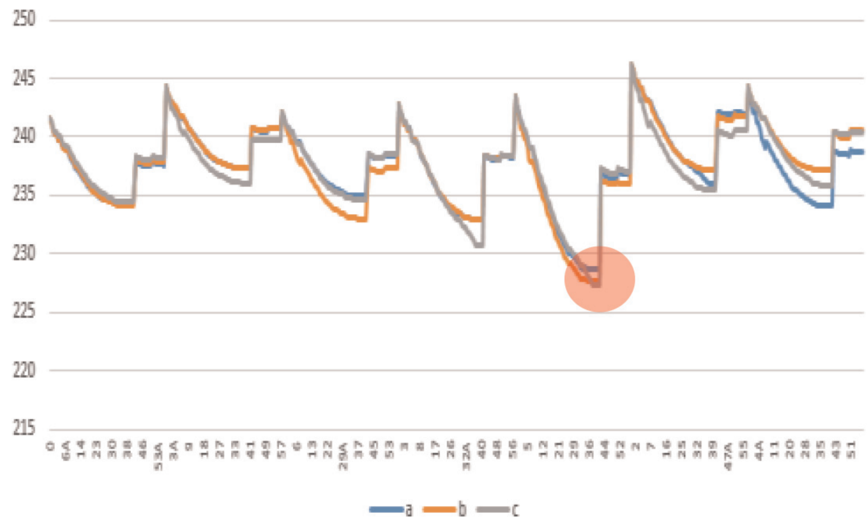

Figure 12.
Voltage variation in the nodes [V] (final situation—balanced case).

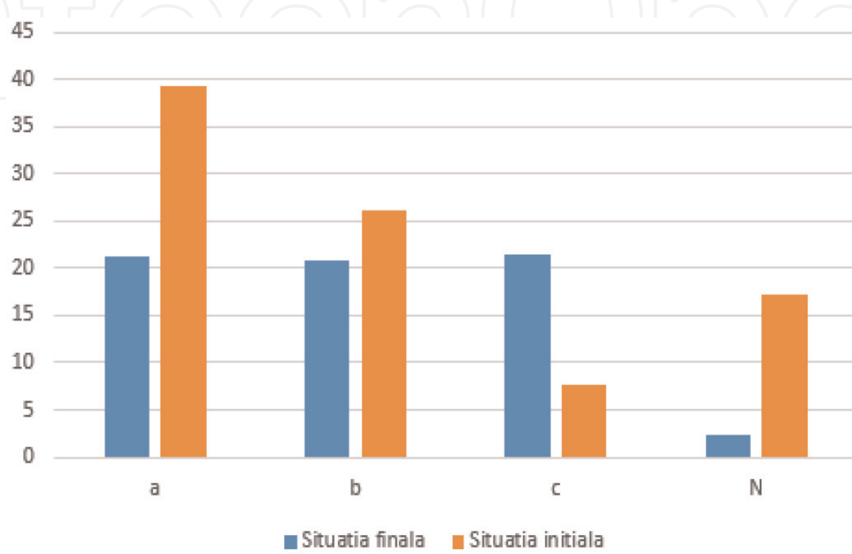

Figure 13.
Total energy losses [kWh] (unbalanced case vs. unbalanced case).

Day	Unbalanced case	Balanced case	δΔWT [kWh]
	ΔWT [kWh]	ΔWT [kWh]	
MI	10.10	7.18	2.92
JO	12.93	9.71	3.22
VI	11.29	8.49	2.8
SA	15.27	11.19	4.08
DU	16.57	11.88	4.69
LU	14.56	10.32	4.24
MA	11.99	9.59	2.4
Total	**92.70**	**68.37**	**24.33**

Table 4.
Energy losses during the analyzed period.

presented in **Figure 12**. A substantial reduction of the energy losses was obtained on the neutral conductor (approximately 86.21%, from 17.26 to 2.38 kWh).

3. Demand response in active distribution networks

While all Demand response programs encourage consumer demand flexibility by shifting or reducing load in critical time intervals, for lowering market prices and improving operation conditions in electricity transmission and distribution networks, there are several ways to achieve this goal. The literature distinguishes two main types of DR: controllable (incentive-based) and price-based [14].

The former are most restrictive DR approaches and they frequently involve direct or indirect load control, according to the curtailment level required by the coordinating entity of the program (usually, the DSO or an aggregator). Direct Load Control (DLC) is remotely enforced by the coordinating entity, a task that requires bidirectional real-time communication with the consumer site. On the other hand, price-based DR relies on consumer response to electricity price variations.

3.1 Demand response management algorithm for ADN

The involvement of residential consumers in DR programs is currently in its incipient stage. Several problems contribute to this situation. The first are the demand level of individual consumers and the need for aggregators. Residential consumers have much lower demand, compared to other consumer categories, such as industry. In rural underdeveloped areas, most consumers achieve less than 1 kW power draw. Because electricity markets require minimum demand reduction biddings of 100 kW and more [8], the participation of residential consumers to DR programs is feasible only to households with higher demand, managed by aggregators who can achieve the minimum DR levels required by the market.

Another key factor is the user comfort. As a general rule, residential consumers are not willing to sacrifice to a great extent their personal comfort in order to better contribute to DR. As such, a household will try to set and accomplish a DR target with minimum effort, while maintaining its comfort requirements (i.e., room air temperature). The process of dynamically optimizing appliance schedule while accounting for pre-set comfort levels, market price variation and DR signals, requires automated algorithms, known as Smart Home Energy Management

Systems (SHEMS) [15]. While the effect of the rebound load on operating frequency is negligible [16], it can be higher regarding network losses and quality of supply.

As described in [17], artificial intelligence algorithms are widely used for managing DR at LV network level. This paragraph describes a DR Management Algorithm for aggregators based on the Particle Swarm Optimization (DRMA), which investigates the effect of rebound load in a LV distribution network, taking into account consumer demand levels, comfort and privacy preferences. The algorithm requires as input the following information:

- network data (topology, length of feeder sections, wire type, consumer phase and pole connection) and load data, given as consumer active and reactive power load profiles with a known (e.g., hourly) sampling: $P_{i,h}$, $Q_{i,h}$, $h = 1...24$;

- the *DR* interval set by the aggregator: $Int_{DR} = [h1, h2], h1, h2 \in [1..24], h1 < h2$;

- the DR signal magnitude for the entire network, *targetDR*, given in percent from the network demand in each hour $h1...h2$;

- the maximum percent reduction from each consumer load i, $maxDR_i$, the same for all DR intervals, a value which consider the consumer comfort preferences, given as the maximum load that can be disconnected upon request. At each time interval h, the actual reduction demand of the aggregator must not exceed the maximum limit for any consumer i ($lDR_{i,h} \leq maxDR_i$, $h \in Int_{DR}$, $i = 1..Nc$);

- the load rebound rate RB_h, which describes the load amount which will be switched back on by the consumers after DR, at hour $h + 1$, given in percent from the reduction at hour h. For modeling consumer behavior uncertainty, the actual value of the rebound can be set randomly in an interval from $[0, RB_h]$.

Based on the consumer load and rebound data, the DRMA determines which consumers are eligible for DR load curtailment, according to their hourly demand. Only consumers exceeding a given load threshold ($P_{i,h} \geq P_{max,h}$, $h \quad Int_{DR}$ $i = 1..Nc$) will be considered for DR. A higher threshold will result into a smaller number of consumers being affected. The scheduling of appliances is performed by each consumer, using its SHEMS and comfort preferences. For privacy reasons, the aggregator receives only the load reduction $lDR_{i,h}$,. For determining the optimal DR signal for each household, the Particle Swarm Optimization algorithm [10] is used. The solutions are encoded as number vectors in which each element describes the *DR* reduction applied to the load of each eligible consumer at hour h, as described in **Figure 14**. Here, n is the number of consumers eligible for DR at hour h, and value 3 for consumer n depicts a 30% DR load reduction.

The fitness function based on which the solutions are evaluated has two factors: minimum active power losses in the LV network, and minimum difference between the expected and obtained load reduction by DR, computed for the hour h for which the PSO algorithm is running. Both are expressed in percent.

Cons. i	*Cons. j*	...	*Cons. n*
2	4		3

Figure 14.
Solution encoding for the PSO algorithm.

$$\min(\Delta P_h + M_{DR,h}), \quad h \in Int_{DR} \tag{6}$$

By this approach, it is expected that the algorithm will search for solutions where $M_{DR,h}$ is close to 0, choosing between them as optimal solution the one with the minimal value of ΔP_h. The active losses in the network ΔP_h are computed using the graph theory, with a procedure consisting of several steps. In the initialization stage of the algorithm, the branch-node connectivity matrix $[A]$ and the reference bus loads for each hour h from the DR interval are computed, using the topology of the network and the consumer data. Next, the real bus loads are determined, by subtracting the loss reduction imposed by the DR signal:

$$P_{bs,x} = P_{ref,bs,x} - P_{\mathrm{DR},bs,x}, \quad bs = 1..n \tag{7}$$

The bus active power loads are converted into bus current injections, using the nominal voltage of the network and the power factor:

$$I_{bs,x} = P_{bs,x}/(U_n \cdot \cos(\varphi_{bs})), \quad bs = 1..Nb \tag{8}$$

The branch current flows on each feeder section (branch) br and phase x are then computed, using matrix A and the bus current vector $[I_{bs,x}]$:

$$[I_{br,x}] = -inv(A) \cdot [I_{bs,x}] \tag{9}$$

The power losses in kW on each section br follow:

$$\Delta P_{br,x} = R_{a,br} \cdot I_{br}^2 \cdot K_{br} \cdot 10^{-3} \tag{10}$$

The K_{br} coefficient is used to account for the losses caused by the current flow on the neutral wire. According to Romanian standards, K_{br} is computed for each branch using the CUF factor (1), considering the phase load variation in each hour, with:

$$K_{br,h} = CUF_{br,h} \cdot \left(1 + 1.5 \cdot \frac{R_{n,br}}{R_{a,br}}\right) - 1.5 \cdot \frac{R_{n,br}}{R_{a,br}} \tag{11}$$

In Eqs. (6)–(11), $P_{bs,x}$—the aggregate active power draw in bus bs and phase x (x is a, b, c or abc), during DR; $P_{ref,bs,x}$—the aggregate reference active power draw in bus bs and phase x without DR; $P_{DR,bs,x}$—the aggregate active power reduction in bus bs and phase x, during DR; $I_{bs,x}$—the aggregate current draw in bus bs, on phase x, during DR; U_n—the nominal voltage of the network, $\cos(\varphi_{bs})$—the power factor determined from the aggregate individual active and reactive loads at bus bs; Nb—the number of buses in the network; $R_{a,br}$, $R_{n,br}$—the resistance on section br, on the active and neutral wire respectively. Powers are given in [kW], currents in [A], and voltages in [kV]. The percent active losses in the network for hour h are obtained by summing all branch losses obtained with Eq. (10) and dividing the result by the power infeed of the network:

$$\Delta P = \left(\sum_x \Delta P_{br} \middle/ \left(\sum_x P_{bs} + \sum_x \Delta P_{br}\right)\right) \cdot 100 \tag{12}$$

On the other hand, he difference between the expected and obtained load reduction by DR, $M_{DR,h}$, uses the sum of all differences between the aggregate bus power draws, in absence of and during DR (Eq. (13)).

$$M_{DR} = \left(1 - \sum_{x,\, IntDR} P_{bs,x} \Big/ \sum_{x,\, IntDR} P_{ref,bs,x}\right) \cdot 100 \tag{13}$$

In Eqs. (7)–(13), the hourly index h was omitted for simplicity. The solution which minimizes Eq. (6) is the optimal *DR* dispatch among the eligible consumers for hour h. The PSO algorithm is executed for each hour from the *DR* interval, with the bus loads updated to account the hourly demand and the rebound after the *DR* signal from the previous hour has ended. The block diagram of the DRMA algorithm is given in **Figure 15**.

3.2 Case study

The DRMA was tested on a real Romanian distribution network from a rural area, namely network T2, from **Figure 16**. The main characteristics of the network (number of poles or buses; cable type and cross-section; feeder section lengths; number; type (single phase/three phase) and connection phase of consumers) are indicated in **Table 5**. The load profiles for all the consumers are provided by a Smart Metering system. The hourly load profile of the entire network, on each of the three phases, is given in **Figure 17**.

Analyzing the load profile of the network from **Figure 17**, the Int_{DR} interval was set as $h1 = 18$, $h2 = 22$, for a *DR* interval of 5 h, for the evening peak load time. In **Tables 6–8** are given the results corresponding to the following scenarios:

- Ref—the reference case, where no *DR* request is enforced in the network, and the demand varies according to **Figure 17**;
- DR00—*DR* with 0% rebound, the ideal case, where the load disconnected because of the DR signal is not switched back on later;
- DR50—*DR* with minimum 20% and maximum 50% rebound, when maximum half of the load disconnected in hour h will return at the network buses in $h + 1$.

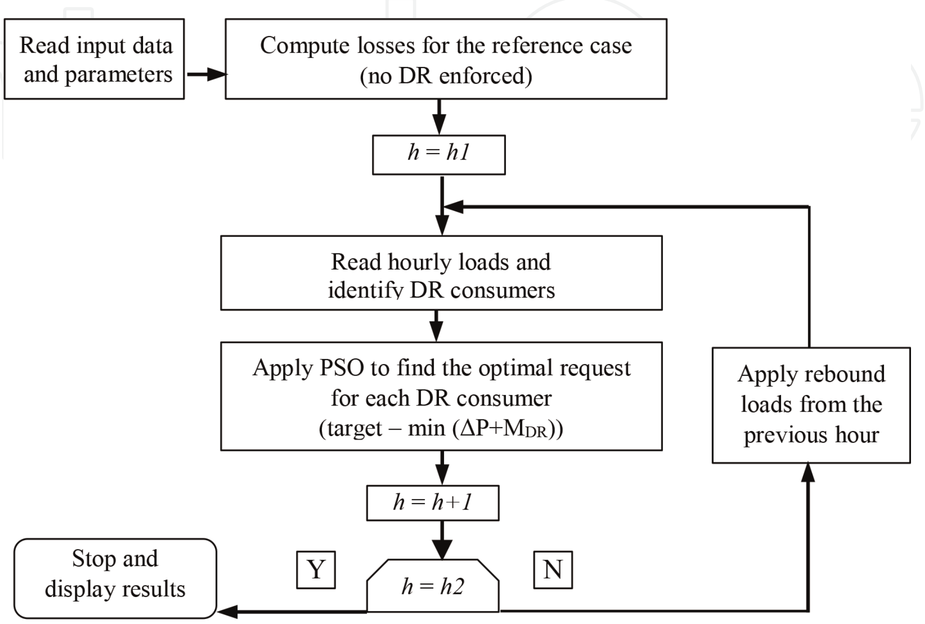

Figure 15.
The block diagram of the DRMA.

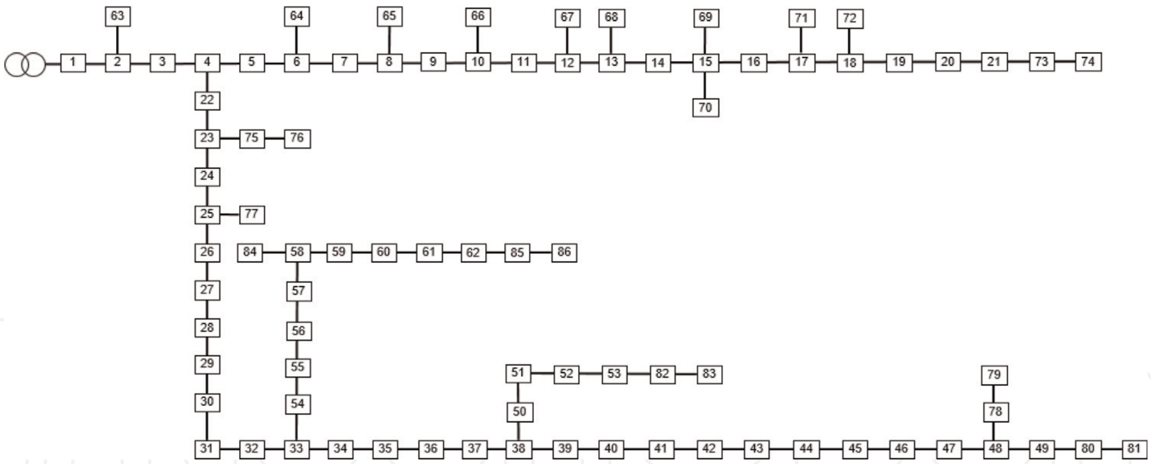

Figure 16.
The topology of the test network T2.

Number of poles	Total length [m]	Connection phase				Wire data		
		a	b	c	abc	Type	Section [mm^2]	Length [m]
86	3440	20	21	19	0	OHL Ol-Al	3 × 50 + 35	3440
		60						

Table 5.
Input data for test network T2.

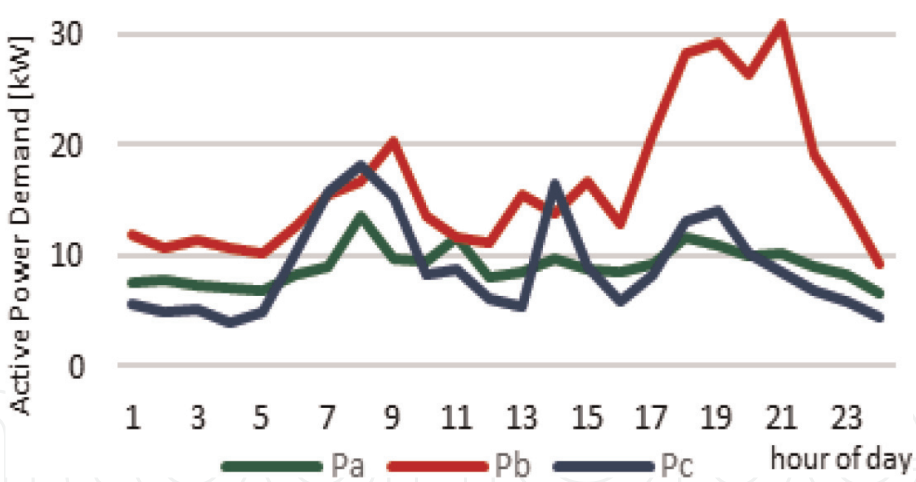

Figure 17.
Phase load in the network, on the three phases.

h	P_a [kW]	P_b [kW]	P_c [kW]	ΔP_{abc} [kW]	ΔP_a kW]	ΔP_b [kW]	ΔP_c [kW]	ΔP_{abc} [%]	ΔP_a [%]	ΔP_b [%]	ΔP_c [%]
18	11.596	28.215	13.028	**3.486**	0.820	1.869	0.797	**6.19**	6.60	6.21	5.76
19	10.981	29.093	14.132	**4.079**	0.810	2.366	0.902	**7.00**	6.87	7.52	6.00
20	10.087	26.366	10.229	**4.029**	0.761	2.735	0.533	**7.95**	7.01	9.40	4.96
21	10.285	30.877	8.494	**7.211**	1.043	5.695	0.474	**12.68**	9.21	15.57	5.28
22	9.050	19.016	6.806	**2.709**	0.789	1.704	0.216	**7.21**	8.02	8.22	3.08

Table 6.
Results for the reference case without DR (scenario ref).

h	P_a [kW]	P_b [kW]	P_c [kW]	ΔP_{abc} kW]	ΔP_a [kW]	ΔP_b [kW]	ΔP_c [kW]	ΔP_{abc} [%]	ΔP_a [%]	ΔP_b [%]	ΔP_c [%]
18	9.256	24.791	10.860	**2.249**	0.446	1.313	0.490	**4.77**	4.59	5.03	4.32
19	9.529	23.739	12.821	**2.375**	0.528	1.211	0.636	**4.90**	5.25	4.85	4.73
20	9.339	20.598	9.750	**2.066**	0.496	1.167	0.403	**4.95**	5.04	5.36	3.97
21	9.639	24.074	8.494	**3.355**	0.697	2.287	0.371	**7.36**	6.74	8.68	4.18
22	7.451	15.382	6.806	**1.441**	0.412	0.838	0.191	**4.64**	5.24	5.17	2.73

Table 7.
Results for the case DR with no rebound (scenario DR00).

h	P_a [kW]	P_b [kW]	P_c [kW]	ΔP_{abc} [kW]	ΔP_a [kW]	ΔP_b [kW]	ΔP_c [kW]	ΔP_{abc} [%]	ΔP_a [%]	ΔP_b [%]	ΔP_c [%]
18	9.499	24.791	10.620	**2.234**	0.467	1.309	0.457	**4.74**	4.69	5.02	4.12
19	10.326	24.781	13.436	**2.699**	0.601	1.372	0.726	**5.27**	5.50	5.24	5.13
20	9.585	21.456	10.430	**2.374**	0.588	1.296	0.490	**5.41**	5.78	5.70	4.48
21	10.241	25.070	8.425	**3.830**	0.853	2.607	0.370	**8.05**	7.69	9.42	4.21
22	8.255	16.265	6.835	**1.773**	0.543	1.029	0.202	**5.35**	6.17	5.95	2.87

Table 8.
Results for the case DR with 20–50% rebound (scenario DR50).

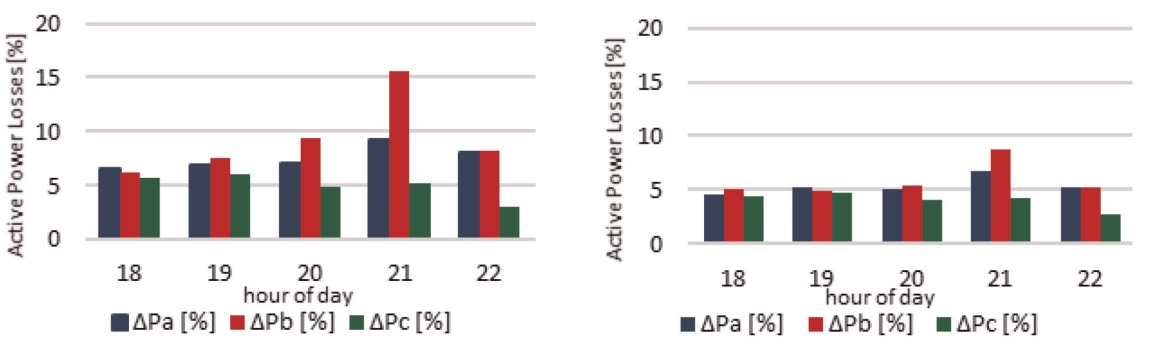

Figure 18.
Phase active power losses in scenario Ref (left), DR00 (right).

The minimum hourly load for DR-eligible consumers was set at 0.8 kW. This setting resulted in 13–23 consumers affected by the *DR* signal in the DR50 scenario, the number varying in each hour according to the bus and rebound loads. **Figure 17** shows that the phase loads are highly unbalanced, which results in higher power losses in the network, due to the excessive loading of phase *b* and the neutral wire current flow. By optimally dispatching the *DR* signal across the network in each hour, the DRMA algorithm is expected to also reduce the phase load unbalance from the reference case.

The results show that the active power losses decrease in the *DR* scenarios, more if there is no rebound load in the 19:00–22:00 interval. The best effect can be seen at the peak hour 21:00, when the losses drop from 12.68% in the reference case to 7.36% in the DR00 scenario and 8.05% in the DR50 scenario respectively. The phase loss distribution in the three scenarios, depicted in **Figure 18**, shows that a secondary effect of *DR* an improved balancing of the phase loss values. The load variation for scenario DR50 is similar to case (b).

4. Voltage control in active distribution networks

4.1 Problem statement

The voltage control strategies are sometimes a key performance indicator in ADN. In the literature, this problem is solved using pseudo-measurements. Due to the intermittent and unpredictable behavior of consumptions and distributed energy sources, the generation excess could lead to a reversed power flow, from the consumers to the supply external point [18, 19]. This drawback requires a real-time effective voltage control strategy [20], particularly under islanded operation modes, to obtain the best solutions, with reliable effects on the minimization of energy losses, and energy efficiency improvement [21, 22]. Our proposed approach uses Smart Metering information (active and reactive daily load curves).

The objective of the optimization procedure is to assess the influence of renewable sources (i.e., wind turbines) into an ADN in order to improve the voltage at the end-users and to minimize the active power losses, considering the technical constraints. The proposed approach was formulated as:

$$MinF([U],[\Psi]) = \min\left(\Delta U_{ADN}^{h}\right) + \min\left(\Delta P_{ADN}^{h}\right) \tag{14}$$

where: *minF*—the goal function;
$[U]$—the voltage magnitude vector;
$[\Psi]$—the transformers tap changing matrix;
ΔU—the voltage drops;
$h = 1..T$, the hourly measurement interval for the steady state;
ΔP—the active power losses.

The equality constraints coincide with the bus power balance in the ADN. For a given bus $k = 1,\ldots, N$, a time sample h, and an operating states j, the equations are:

$$P_{h,k,j}^{3ph} + jQ_{h,k,j}^{3ph} = \overline{U}_{h,k,j} \cdot \overline{I}_{h,k,j}^{*} \tag{15}$$

where the active and reactive power are a sum of the three phases of the ADN:

$$P_{h,k,j}^{3ph} = P_{h,k,j}^{a} + P_{h,k,j}^{b} + P_{h,k,j}^{c};\ Q_{h,k,j}^{3ph} = Q_{h,k,j}^{a} + Q_{h,k,j}^{b} + Q_{h,k,j}^{c} \tag{16}$$

The mathematical model has the following inequality constraints:

1. Voltage allowable limits:

$$U_{h,k,j}^{\min} \le U_{h,k,j} \le U_{h,k,j}^{\max} \tag{17}$$

2. Thermal limits of the branch loadings:

$$S_{h,k,j} \le S_{h,k,j}^{\max} \ \ or \ \ I_{h,k,j} \le I_{h,k,j}^{\max} \tag{18}$$

3. The allowable reactive power of DG sources must be constrained as:

$$Q_{h,\min}^{wind} \le Q_{h}^{wind} \le Q_{h,\max}^{wind} \tag{19}$$

4. The constraints for the transformer tap changer must be in accordance with the proposed strategy, and are the following:

$$\Psi^h_{\min} \le \Psi^h_{k,j} \le \Psi^h_{\max} \tag{20}$$

where U^{min}, U^{max}—the inferior/superior voltage limit; $I_{h,k,j}$—the branch current value; I^{max}—the branch ampacity value; $S_{h,k,j}$—the branch apparent power; S^{max}—

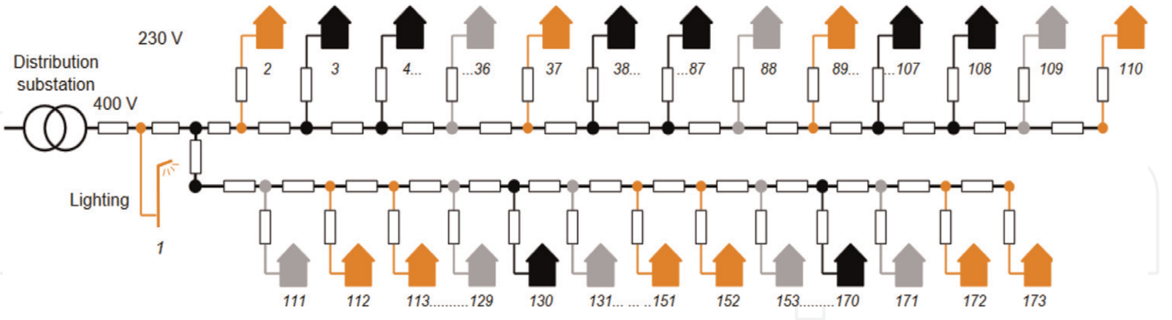

Figure 19.
Single-line diagram of the LV distribution network.

Hour/cases	Pole no. 88			Pole no. 110		
	I	II	III	I	II	III
1	0.3684	0.3924	0.3925	0.3673	0.3913	0.3915
2	0.3701	0.3928	0.3929	0.3691	0.3919	0.3919
3	0.3721	0.3933	0.3933	0.3712	0.3924	0.3925
4	0.3718	0.3932	0.3932	0.3708	0.3923	0.3923
5	0.3719	0.3933	0.3933	0.3710	0.3924	0.3924
6	0.3764	0.3947	0.3947	0.3755	0.3939	0.3939
7	0.3715	0.3936	0.3935	0.3705	0.3926	0.3925
8	0.3681	0.3927	0.3927	0.3670	0.3916	0.3916
9	0.3653	0.3918	0.3920	0.3641	0.3907	0.3909
10	0.3640	0.3913	0.3916	0.3628	0.3901	0.3905
11	0.3584	0.3896	0.3897	0.3571	0.3883	0.3884
12	0.3617	0.3902	0.3907	0.3605	0.3890	0.3896
13	0.3591	0.3894	0.3902	0.3579	0.3882	0.3891
14	0.3600	0.3900	0.3907	0.3587	0.3887	0.3895
15	0.3593	0.3897	0.3905	0.3580	0.3884	0.3893
16	0.3646	0.3914	0.3917	0.3634	0.3902	0.3906
17	0.3591	0.3897	0.3905	0.3578	0.3884	0.3892
18	0.3534	0.3883	0.3885	0.3519	0.3868	0.3869
19	0.3583	0.3900	0.3901	0.3568	0.3886	0.3887
20	0.3628	0.3914	0.3917	0.3615	0.3901	0.3904
21	0.3561	0.3906	0.3898	0.3545	0.3892	0.3882
22	0.3482	0.3895	0.3880	0.3462	0.3879	0.3861
23	0.3493	0.3880	0.3882	0.3474	0.3861	0.3863
24	0.3642	0.3917	0.3920	0.3629	0.3905	0.3908

Table 9.
Voltage magnitude for the two representative busses [kV].

Case	W_{load} [kWh]	ΔW_{loss} [kWh]	ΔW_{loss} [%]	Energy savings [kWh]
Case I (base)	442.47	78.95	15.14	521.42
Case II (DG connected)	442.47	62.36	12.35	504.83
Case III (DG + AVR)	442.47	61.13	12.13	503.60

Table 10.
Comparison between the simulation cases.

the maximum apparent power on branch; Q^{wind}—the reactive power from the DG source; Q_{min}, Q_{max}—the allowable reactive power limits; Ψ—the tap position of the transformer.

4.2 Case study

The voltage control approach proposed above was tested on a real ADN with 163 residential consumers, presented in **Figure 19**. It must be highlighted that the tested ADN already includes two connected small-scale renewable sources.

In order to demonstrate the capabilities of the proposed voltage control strategy, three scenarios for simulation using MATLAB environment were considered:

- First, the base case (Case I) without small-scale sources and AVR control (with the initial tap position).

- The second case (Case II) considers the two real wind generators (2×5 kW) connected into the AND.

- The last case (Case III) uses the voltage control strategy (14)–(20).

Case II is proposed for assessing the influence of the DG sources on the voltage and power losses magnitude in a real ADN. In addition, Case III follows the improvement of voltage magnitude based on a coordination between the generation of the distributed sources and the automation distribution devices.

The results regarding the voltage magnitude in the three considered cases, are given in **Table 9**, only for representative connected points of DGs: pole no. 88 and the last ADN bus, pole no. 110. The daily energy losses are presented in **Table 10**, where W_{load} is the total energy required by the consumers.

It can be observed in **Table 10** a reduction of energy losses, with over 3%, from 15.14 to 12.13% with energy savings of about 17.82 kWh for the entire ADN.

5. Conclusions

The active distribution networks will be developed based on the improved actual infrastructure with the main advantage regarding the bidirectional communication between supplier and consumers. This makes possible a supervising and control at an advanced level of the smart systems which will be integrated inside their.

The chapter aimed to highlight the advantages of introducing the smart systems in the active distribution networks that lead to an optimal operation regarding the phase load balancing, voltage control and demand response with benefits for both DSO and consumers. The offered solutions are based on the information provided by the smart meters, these being an important link between the consumers, dispatch centers of DSOs, renewable sources, and the smart systems integrated in the networks. The case studies based on the pilot active distribution networks belonging to a DSO from Romania, emphasized the importance of integrating the smart devices so that the control to make easy and the transition to self-control networks to be smooth. The obtained results allow us to expect that in a short time the expression "active" will be used for all distribution networks.

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