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POSIBILITIES OF LOAD CURVES MODELLING IN ELECTRIC ENERGY DISTRIBUTION NETWORKS

BY

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Abstract. Power consumption is becoming fundamental for an efficient management, planning and operation of electric energy distribution networks (EDN). Actually, in our country, the medium voltage (MV), but especially the low voltage (LV) distribution networks are generally characterized through the absence of technical monitoring possibilities. The paper proposes a new approach for consumption mathematical modelling (active and reactive load curves) using reduced measurements attached to typical load profile (TLP) of different consumer categories. Finally, in order to validate the performance of proposed load modelling methodology, the obtained daily load curve of a real EDN from Iasi is presented. After the results analyse it can be seen small errors between modelled and real load (<3%) which demonstrates the accuracy of proposed approach and confidently use to steady state computation.

Key words: load modeling; typical load profile; distribution networks.

1. Introduction

For an efficient EDN operation and a rational economic and financial management of the power distribution companies, one of the requests that must be fulfilled is the knowledge of power and energy demand, in *where*, *when* and *how much* terms (Georgescu *et al.*, 2009). The electricity consumption has a

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significant influence on costs, being imperative to know both real power consumption and power use efficiency by consumers (Blanc *et al*., 2011).

In our country, MV and mainly the LV electric energy network have a big number of components that are spread on large areas, have a relatively high density and are characterized, generally, by the absence of the technical possibilities for load monitoring. Generally, the EDN are mainly operated in radial configuration and in most cases online measurements being limited to the main substations, and feeders leaving those substations supply power to customers connected through MV/LV transformers. Accordingly, modern power distribution companies need accurate load information for EDN planning and operation, steady state optimization, load management, etc. (Neagu *et al*., 2012).

At the industrial consumers load curves can be known because they are equipped with electronic meters, but this is not the case of households and tertiary consumers (Georgescu *et al*., 2009). Actually, last ones represent the main percentage of territorial distribution unit clients and their metering with electronic counters is uneconomical (unprofitable) taking into account the small quantity of consumed energy. To consider these consumer categories, their consumption representation by an adequately model is necessary. The TLP can be defined as a commonly used model of electric energy consumer. In our country, these profiles are made in 24 hourly levels form, the loads being expressed in per unit (p.u.), related to average load of the recorded and processed daily load curves (Neagu *et al*., 2011, Georgescu *et al*., 2012).

A review of the literature revealed two types of methods for load curve modelling focused on electric energy consumption characteristics (Neagu, 2014): improved classical (statistical probabilistic) and modern artificial intelligence methods (fuzzy and clustering techniques, artificial neural networks, genetic algorithm, etc.). Therefore, Carmona *et al*., (2010) have proposed the load curve modelling approach based on the least-squares optimization problem, aimed at error minimizing between a reference and modelled daily load curve. However, according to Sharifian *et al*., (2012), Apolinario *et al*., (2009), for load curve mathematical modelling the consumers TLP and individual average load demand are used. For substations daily load profile modelling Tawalbeh *et al*., (2008) propose to use the daily variation factors. Also, for EDN load modelling a fuzzy clustering technique (Tsekouras *et al*., 2008) and artificial neural network methods (Gerbec *et al*., 2005; Fidalgo, 2008; Puthooran *et al*., 2009) are used. Load curve modelling using genetic algorithm is used by Gargeya *et al*., (2013).

This paper proposes a relatively simple load curve mathematical modelling approach based on a limited set of measured data added to TLP of all considered consumers, supplied from EDN substation. The results showed that the proposed method allows a proper mathematical modelling of load curves on electrical networks. All modelled load curves were stored in a database and can already been used for the following studies: voltage regulation; load profiling;

peak load determination for different consumer categories; energy and power losses evaluation; power flow computation and optimization, etc.

2. Database with Typical Load Profiles

Although it can be built a significant number of typical load profiles, it was observed that many consumers have common daily load curve patterns. Thus, proper portfolio with daily load curve for every EDN branch requires the knowledge of TLP number and specificity, which will form the database (Georgescu *et al.*, 2009). The criteria which must be used in selecting a TLP representative are the following: the TLP are modelled after a record of at least one year; every TLP must represent a relatively homogenous number of consumers and must be distinct from other TLP; the TLP set must cover a large number of household and tertiary (small) consumers; when using the consumption sampling, the criteria which consider that a TLP is associated with a certain consumer type must be very clearly mentioned, in order to facilitate a simple use in operation; the TLP number retained in database must be small.

In order to identify different active and reactive TLP for different consumer categories supplied from EDN, Georgescu *et al.*, (2009), propose an extended consumers sounding system. This goal requires a significant effort concerning both the staff involved and measuring or recording meters. The high cost associated with a measurements campaign makes the process of all consumers sounding to be difficult (Neagu *et. al.*, 2011).

Bompard *et al.*, (2000), propose a method for TLP determination using stratified sampling and Georgescu *et al.*, (2012) propose an alternative approach that gives lesser importance of predetermined classifications, leaving freedom the classification procedure to extract so many consumer categories as necessary, up to a predetermined limit. In this alternative, the main classification criterion is the pattern of the daily active and reactive recorded loads. This procedure belongs to the self-organization algorithms category (unsupervised learning) and the best was SOFMs (Self Organizing Feature Maps) algorithm applied to the Kohonen neural networks, because has a net structure, when the nodes contain one neuron which represents a class or category.

Based on the consistent number of records carried out on LV substation bars of urban EDN, between 2003 and 2012, a TLP database (for different consumer categories at working and weekend days from winter and summer state) was created. For database size reduction, in a first step the correlation coefficients between active and reactive load curves were computed; the values other than 0.91 to 1.0 were considered random (exceptions) cases and were excluded from the database. To increase the accuracy of TLP determination and to avoid the introduction in database the TLP which deviate from the general trend, in second step a Kohonen self-organizing algorithm was used. TLP which correspond to aforementioned conditions constitute database (Neagu, 2014).

3. Active and Reactive Load Curves Mathematical Modelling Approach

Having available the database with TLP, active and reactive daily load curves of EDN nodes in summer/winter working and the weekend days can be modelled by associating between consumers TLP and consumption nodes structure with a small number of recorded information from the analysed network nodes. The information that can be recorded is:

1. *The measured current from a node in any daily hour*. The active and reactive loads, at hour t from the daily load curves, allocated in the node *n*, are determined with the following relations:

$$\begin{aligned} P_{n,j}(t) &= \sqrt{3}U_n I_{n,j}(k)\cos\phi_j^T(k)\frac{P_j^T(t)}{P_j^T(k)}, \\ Q_{n,j}(t) &= \sqrt{3}U_n I_{n,j}(k)\sqrt{1-\cos^2\phi_j^T(k)}\,\frac{Q_j^T(t)}{Q_j^T(k)}, \end{aligned} \quad \left(t=\overline{1,24}\right) \tag{1}$$

where: $P_{n,j}(t)$, $Q_{n,j}(t)$ represent active and reactive power in node *n*, for state *j*, at hour *t*; $I_n(k)$ – the measured current in node *n*, for state *j*, at hour *k*; $P_j^T(t)$, $P_j^T(k)$, $Q_j^T(t)$, $Q_j^T(k)$ are, respectively, the active/reactive load average value from TLP for state *j* at hours *t* and *k*; $\cos\phi_j^T(k)$ – the power factor that corresponds to the active and reactive TLP for state *j*, at hour *k*; U_n – the nominal voltage of EDN.

2. *The active energy that flows in 24 hours in the node.* The active and reactive loads, at hour t from daily load curves, are determined with

$$P_{n,j}(t) = \frac{W_{n,j}}{24}P_j^T(t);\;\; Q_{n,j}(t) = P_{n,j}(t)\sqrt{\frac{1}{\cos^2\phi_j^T(t)}-1},\;\left(t=\overline{1,24}\right) \tag{2}$$

where: $W_{n,j}$ is active energy that flows in 24 hours in node *n*, for state *j*, and $\cos\phi_j^T(t)$ – the power factor of the active and reactive TLP for state *j*, at hour *t*.

3. If it is known only the transformer average loading, the active and reactive load for state *j*, at the hour *t*, can be estimated with following relations:

$$P_{n,j}(t) = \overline{k}_{zj_P} S_n P_j^T(t);\;\; Q_{n,j}(t) = \overline{k}_{zj_Q} S_n Q_j^T(t),\;\left(t=\overline{1,24}\right), \tag{3}$$

where: $P_j^T(t)$, $Q_j^T(t)$ are, respectively, the active and reactive load average value from TLP, in state *j*, at hour *t*, corresponding to main EDN branch; $\overline{k}_{zj_P}$, $\overline{k}_{zj_Q}$ – statistical average values of transformers loading coefficients from the MV/LV substation, at a medium daily active and reactive load, in state *j*; S_n – nominal apparent power of the MV/LV substation transformer.

If the daily load curves estimation from EDN nodes is realized with (3), depending on the average load coefficient ($\overline{k}_{zj} = M_i / N_i$) and standard deviation ($\sigma = \sqrt{1/(N_i - 1)\left(S_i - N_i \overline{k}_{zj}\right)^2}$) the values of the load coefficients, $\overline{k}_z$ must fulfil the following restriction:

$$\overline{k}_z \le \overline{k}_{zj} + 3\sigma_j\,, \tag{4}$$

where M_i is the load coefficients sum for N_i nodes; σ_j – the load coefficient standard deviation from TLP in the state j; S_i – the squares sum of load coefficients for all N_i nodes, in the state j.

The load factors verification must be achieved in order to satisfy the following inequality:

$$\overline{k}_{\max} \le \frac{k_{\max}}{P^T_{j\max}}\,, \tag{5}$$

where $k_{\max}$ is the real loading coefficient of network at peak load and $P^T_{j\max}$ – the maximum value from active TLP in state j.

To increase the accuracy on active and reactive load modelling in the EDN nodes, the load curves can be corrected to achieve the hourly active power balance at network area (feeders) or to entire network level, satisfying the equality between injected powers and those absorbed by consumers:

$$\gamma_{P,j} P_j(t) - \sum_{n=1}^{m} P_{n,j}(t) = 0; \quad \gamma_{Q,j} Q_j(t) - \sum_{n=1}^{m} Q_{n,j}(t) = 0, \quad \left(t = \overline{1,24}\right), \tag{6}$$

where: m is the number of nodes from the network; $\gamma_{P,j}$, $\gamma_{Q,j}$ – coefficient that is influenced by the active power losses from the lines and transformers; $P_j(t)$, $Q_j(t)$ – the active and reactive power injected in the network, in the state j, at the hour t; $P_{n,j}(t)$, $Q_{n,j}(t)$ – active load modelled with relations (1), (2) or (3), for node n, in the state j, at the hour t.

Generally, relations (6) are not fulfilled and must be made corrections on the modelled active and reactive loads with the following expressions:

$$\left.\begin{aligned} \Delta P_{n,j}(t) &= \frac{\left[\gamma_{n,j} P_j(t) - \sum\limits_{n=1}^{m} P_{n,j}(t)\right] P_{n,j}(t)\left[1 - \omega_{n,j}(t)\right]}{\sum\limits_{n=1}^{m} P_{n,j}(t)\left[1 - \omega_{n,j}(t)\right]}, \\ \Delta Q_{n,j}(t) &= \frac{\left[\gamma_{n,j} Q_j(t) - \sum\limits_{n=1}^{m} Q_{n,j}(t)\right] Q_{n,j}(t)\left[1 - \omega_{n,j}(t)\right]}{\sum\limits_{n=1}^{m} Q_{n,j}(t)\left[1 - \omega_{n,j}(t)\right]}, \end{aligned}\right\} \quad \left(t = \overline{1,24}\right), \tag{7}$$

where $P_{n,j}(t)$ and $\Delta Q_{n,j}(t)$ are, respectively, modelled active and reactive load to the node n, in the state j, at the hour t and $\omega_{n,j}(t)$ – the truthfulness coefficient.

Taking into account de aforementioned, Fig. 1 presents the flowchart of proposed load curve modelling algorithm, wherein n represent the number nod; $n_{\max}$ – the maximum number of nodes; T = 1 .. 24 h; b = 1 – the correction coefficient of the load curve correction at substation level and for feeder level otherwise; m = 1, 2 or 3 – a coefficient for the used load modelling methodlogy, respectively: m = 1 – the load curve modelling using the measured current at any hour with relation (1); m = 2 – the load curve modelling using the daily

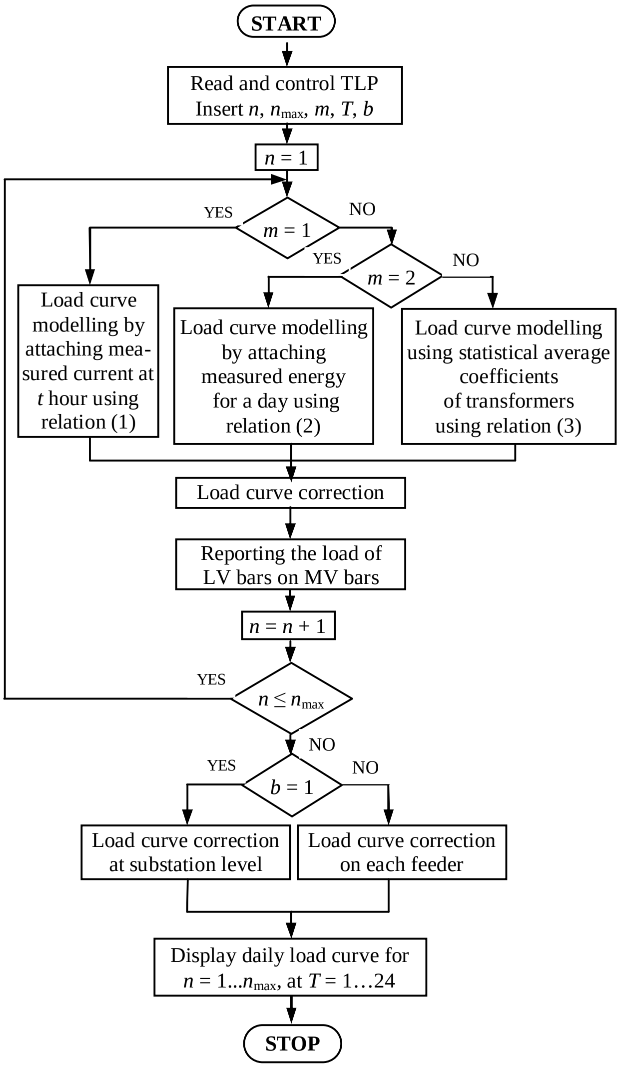


Fig. 1 – The flowchart of load curve mathematical modelling proposed algorithm.

energy with relation (2); m = 3 – the load curve modelling using statistical average coefficients of transformers with relation (3).

All the three possibilities above mentioned concerning the active and reactive loads allocation from the EDN network nodes lead to low errors. Applying the corrections to the nodal loads, in order to satisfy the active and reactive balance of powers, the modelled load curves lead to the real ones, the errors being under 3%.

4. Case Example. Results and Discussion

To test and validate the proposed methodology for daily load curves modelling, a public EDN which supplies a significant number of households and a small number of tertiary consumers (school, hotel, and hospital) were analysed. The single-line diagram of the real test network is shown in Fig. 2.

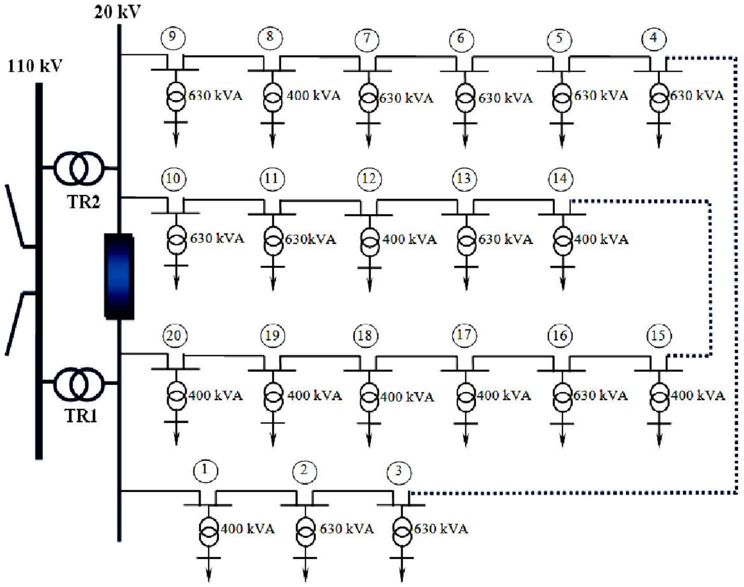


Fig. 2 – The single-line diagram of real analysed EDN (20 kV).

The public EDN operate in radial configuration and feeds through MV cables *i.e.* A2YSY, ACYABY, and NAHKBA (150 mm^2 or 185 mm^2), 20 power substations with 400 kVA and 630 kVA transformer. The 110/20 kV station is monitored with SCADA, having at disposal the load for the two transformer and for all MV departure (20 kV).

The active and reactive load curves mathematical modelling in EDN substation was carried out using the methodology described in the previous section, with a software application based on the algorithm shown in Fig.1, proposed by the authors. The active and reactive powers, daily load curves were modelled for a working day (Wednesday, December 11), considered the peak loaded day of winter state 2013. The active and reactive load curves were modelled considering the database with TLP for all consumers and by introducing both the consumption structure (in %) in all nodes (substation) of studied EDN and a small number of measurements performed at LV substation bars such as the measured current from a node and the measurement hour, and the active energy that flows in 24 h in the node, respectively (Table 1).

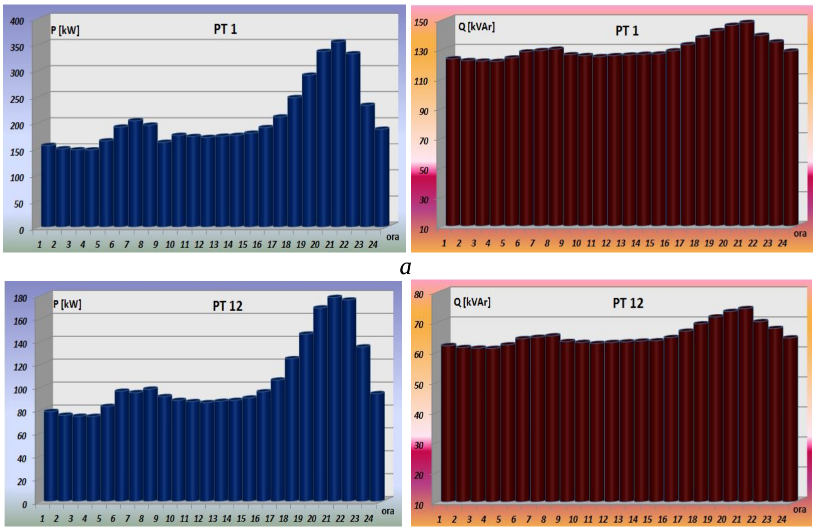
The software application allowed all active and reactive load curves modelling under 24 hourly levels in all LV substation bars of analyzed network. Further, having modelled all daily load curves at LV bars level, these were reported to MV substation bars by considering, for each hourly level of the load curves the active and reactive power losses that occur in transformers. In the second phase, to validate the proposed modelling methodology four electronic meters Alpha ® Power + (Alpha, 2003) on LV bars of four substation (5, 9, 14 and 19) were mounted, for active and reactive load curves recording.

Table 1

The Measurements (Energies and Currents) in Analysed EDS Nodes and Consumption Weights for Each Node in a Working Day on Wednesday December 12, 2013

No. substation	S_n kVA	W kWh	I A	I h	Consumption weights
1	400	4,948	360	17:00	100 % urban household
2	630	3,753	256	17:00	85% urban household; 15% lyceum
3	630	8,100	520	16:00	100% urban household
4	630	3,892	162	17:00	85% urban household; 15% hospital
5	630	3,437	548	18:00	80% urban household; 20% hospital
6	630	4,655	352	18:00	100 % urban household
7	630	2,233	184	18:00	75% urban household; 25% hospital
8	400	4,382	260	18:00	100 % urban household
9	630	630	131	18:00	100 % urban household
10	630	4,981	385	17:00	100% urban household
11	630	3,644	296	20:00	80% urban household; 20% lyceum
12	400	2,573	235	19:00	100% urban household;
13	630	4,012	380	19:00	100% urban household;
14	400	4,326	332	19:00	70% urban household; 20% hospital; 10% lyceum
15	400	3,388	328	19:00	90% urban household; 10% hospital
16	630	1,866	157	18:00	50% urban household; 50% hotel
17	400	1,949	181	19:00	100 % urban household
18	400	3,591	342	19:00	100 % urban household
19	400	1,685	108	17:00	100 % urban household
20	400	4,977	414	18:00	100 % urban household

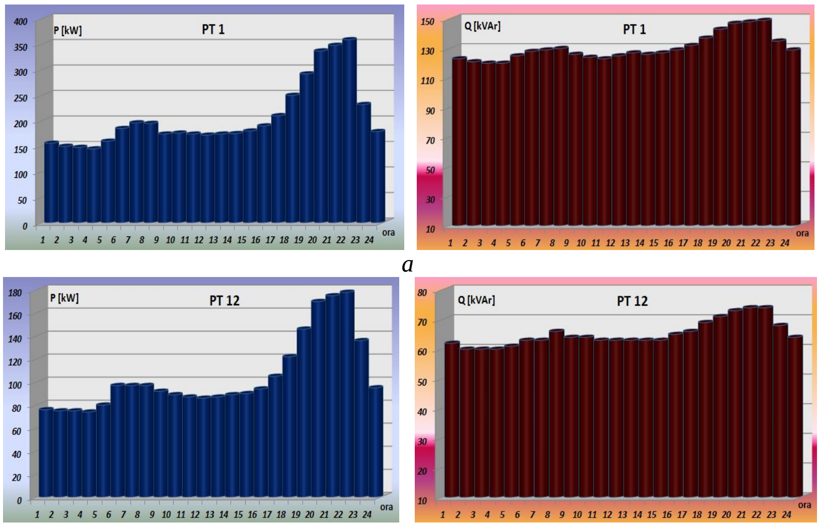
Knowing the real active and reactive load curves at MV station bars and daily load curves mathematically modelled and reported to MV bars of all substations has passed to the next step *i.e.* the correction of modelled load curve using relation (7). To this end, the achievement of active and reactive power balance on the entire MV distribution network, for each hourly level of day, was followed.



a

b

Fig. 3 – Active and reactive daily load curves modelled on LV bars, reported at MV bars for two substation 1 (*a*) and 12 (*b*).



a

b

Fig. 4 – Active and reactive daily load curves corrected on LV bars, reported at MV bars for two substation 1 (*a*) and 12 (*b*).

For example, the daily load curves for substations 5 and 19 of analysed EDN are presented in the two instances aforementioned: the daily load curves modelled and reported at MV bars (Fig. 3) and the daily load curve corrected to achieve power balance of entire EDN analysed (Fig. 4). From the daily load curves analysis, it is found that exist some differences between various hourly levels. Therefore, if the load curves are modelled according to the proposed methodology in this paper, to obtain the daily load curve as close to the real ones, are necessary corrections for achieving active and reactive power balance not of the analysed entire network or area, but as small network portions such as, for example, a single MV distributor.

Fig. 5 shows the active and reactive daily load curves modelled for all nodes of the EDN presented in Fig. 2.

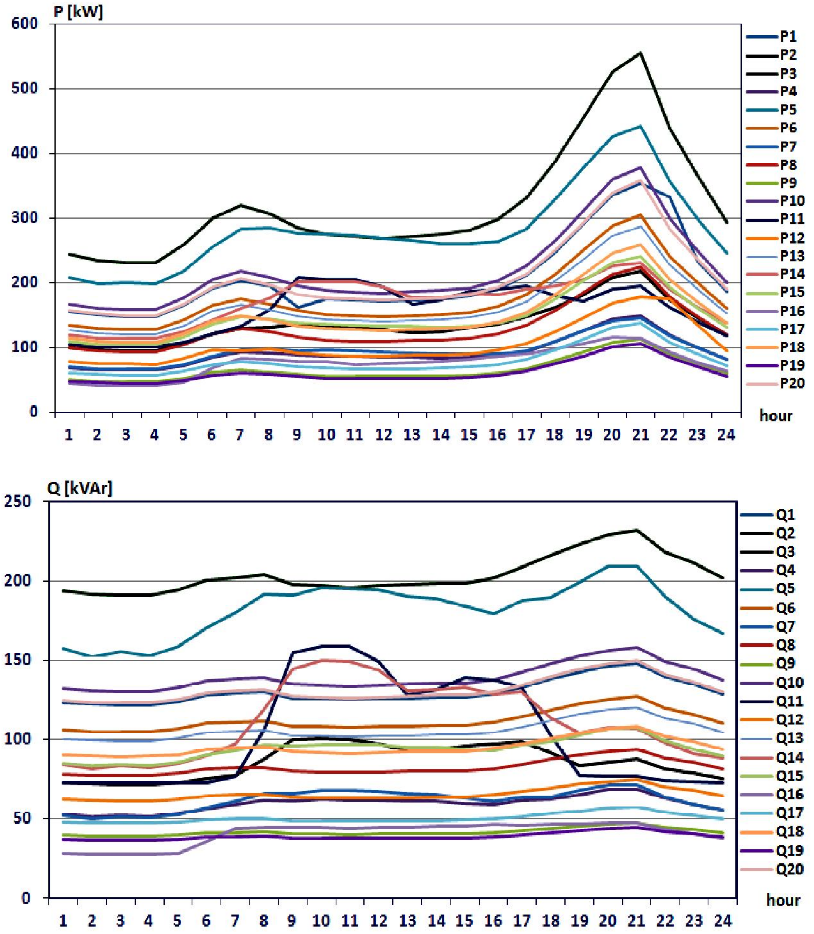


Fig. 5 – Active and reactive load curves modelled for all analyzed EDN nodes.

Taking into account the aforementioned, active and reactive daily load curves mathematical modelled and corrected for the two substations were analysed in comparison with those recorded, the errors being relatively small (less than 3%), as shown in Fig. 6 and Table 2. Following the analysis was found that between the daily load curves mathematically modeled/corrected and real ones are some insignificant differences for EDN steady state computation.

Table 2
The Errors between Real and Modelled Active Daily Load Curve for Two Substation Point (P5 and P19)

Hour	Substation 5			Substation 19		
	P_{real}, [kW]	P_{mod}, [kW]	Error, [%]	P_{real}, [kW]	P_{mod}, [kW]	Error, [%]
1	208.26	205.11	1.535761	46.87	45.68	2.605079
2	198.85	199.86	0.505354	44.96	44.28	1.535682
3	200.01	201.93	0.950825	44.40	45.02	1.377166
4	198.62	196.22	1.223117	44.35	44.68	0.738585
5	218.42	219.03	0.278501	49.53	49.14	0.793651
6	256.26	252.38	1.537364	57.47	58.69	2.078719
7	283.66	284.08	0.147846	61.09	62.97	2.98555
8	284.94	284.53	0.144097	58.57	59.89	2.204041
9	276.59	273.98	0.952624	54.65	53.78	1.617702
10	275.77	278.63	1.026451	52.69	52.14	1.054852
11	272.90	272.55	0.128417	52.03	51.69	0.657767
12	269.46	265.37	1.541244	51.51	52.18	1.284017
13	265.44	265.52	0.03013	52.21	51.79	0.810967
14	261.26	255.41	2.290435	52.70	53.07	0.697192
15	260.63	259.73	0.346514	53.95	54.96	1.8377
16	263.37	264.21	0.317929	57.16	58.12	1.651755
17	284.20	285.89	0.591136	63.29	64.32	1.601368
18	329.00	324.16	1.49309	74.43	73.31	1.527759
19	378.83	382.86	1.052604	87.28	88.41	1.278136
20	426.79	428.79	0.466429	100.94	101.91	0.95182
21	442.36	439.03	0.75849	106.39	107.86	1.362878
22	443.40	445.15	0.393126	108.00	110.78	2.509478
23	298.53	295.39	1.063001	69.99	72.15	2.993763
24	245.44	239.21	2.604406	56.21	57.83	2.801314

Regarding the differences that inevitably occur between modelled load curves with proposed methodology and real load curves, they can be further reduced if the correction is made according to the loads of first section of MV distributor. Technically, this is possible because majority of 110 kV/MV step-down stations which supplies MV distribution networks are generally monitored with SCADA system that can provide information about active and reactive load curve on first section of MV distributor (departure) of monitored MV station.

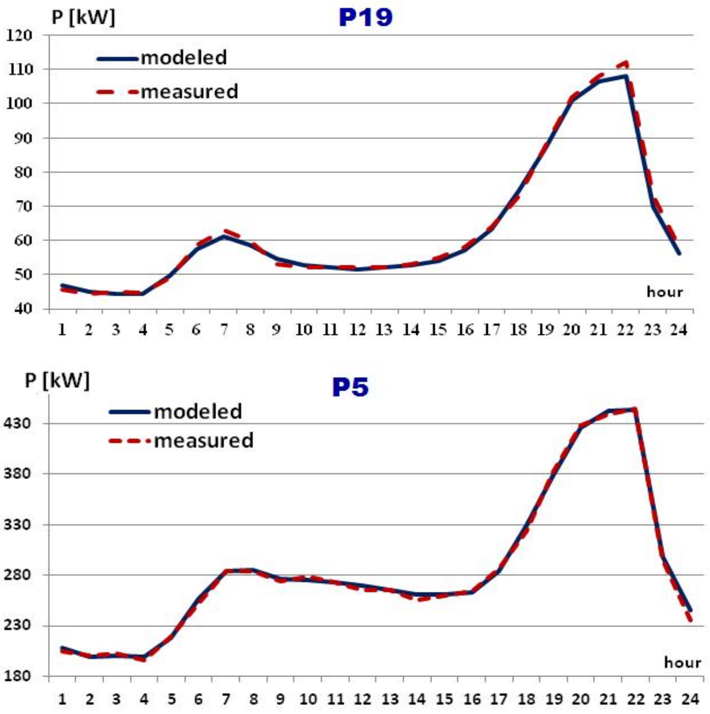


Fig. 6 – Active load curves modelled and recorded for two key points (substation 5 and 19) of the analysed EDN.

4. Conclusions

The paper proposes a new approach for active and reactive load curves mathematical modelling using reduced measurements attached to typical load profile of different consumer categories. The small errors between modelled and real load (<3%) for a real electric energy distribution network, demonstrates the accuracy of proposed approach and confidently use to steady state computation.

In the absence of the monitoring possibilities, the load curves modelling at electric energy distribution network level must be rigorously realized because they represents an essential instrument in proving the decisions and strategies of the territorial distribution companies infrastructure development, the steady state optimization, and electric energy consumption management.

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POSIBILITĂȚI DE MODELARE A CURBELOR DE SARCINĂ ÎN REȚELELE DE DISTRIBUȚIE A ENERGIEI ELECTRICE

(Rezumat)

Modelarea consumului de energie electrică reprezintă un aspect esențial în procesul de management, planificare şi exploatare eficientă a rețelelor electrice de distribuție (RED). La ora actuală, în țara noastră, marea majoritate a RED de medie tensiune (MT), dar în special cele de JT, sunt caracterizate prin absența posibilităților tehnice de monitorizare. În acest context, în lucrare se prezintă o abordare privind modelarea matematică a consumului, respectiv a curbelor de sarcină activă şi reactivă, utilizând profilele tip de sarcină ale consumatorilor, la care sunt ataşate un număr redus de măsurători efectuate direct în rețea. În finalul lucrării, pentru a valida metodologia de modelare matematică a sarcinilor propusă este analizată o RED reală din municipiul Iaşi. În urma analizei rezultatelor obținute se constată erori mici (sub 3%) între sarcinile modelate şi cele efectiv înregistrate, fapt ce demonstrează acuratețea metodologiei propuse şi utilizarea cu încredere a acestor sarcini pentru calculul regimurilor permanente de funcționare.