BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Tomul LX (LXIV), Fasc. 3, 2014
Secţia
ELECTROTEHNICĂ. ENERGETICĂ. ELECTRONICĂ

POWER FLOW OPTIMIZATION USING BOOSTER TRANSFORMERS IN HIGH VOLTAGE DISTRIBUTION NETWORKS

BY

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Received: August 22, 2014
Accepted for publication: September 17, 2014

Abstract. In Romania, the high voltage (HV) distribution networks operate in radial or looped configuration and supply with electricity the 110 kV/MV step-down power station. Trough these stations a big number of residential and tertiary consumers located in urban habitable area are supplied. In this paper, an approach for active and reactive power flow optimization is proposed. By connecting the booster transformer in a real HV distribution network, the active and reactive power losses could be reduced and the voltage levels improved. At the paper end, the results, discussion and conclusion are presented.

Key words: booster transformers; power flow; power losses; voltage level.

1. Introduction

Public distribution systems supply energy to residential, tertiary and small industrial consumers, which are captive consumers. The HV distribution systems for the urban area are built in accordance with the requested consumption and with the configuration of the local area, considering also the MV networks configuration from around. Considering the consumption forecasting for the next 15…20 years, the voltages level in HV distribution

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networks are 110 kV and will increase in future of this level. Generally, the HV distribution networks are in looped configuration, the electric energy supply being realized at the bars of two different injections points (Eremia *et al*., 2006).

The power quality of consumers supplied with electricity represents a demand of a first significance in electrical networks operation process. The bus voltage values depend on the reactive power flow. Also, keeping the voltages values between admissible limits represent an essential problem in the design and operation electric networks. In Romania, the HV distribution systems around the cities with over 250.000 habitants present, generally, a looped configuration. Different sections which composed these rings were built in different stages, according to the development of those cities. For this reason, in many cases, HV distribution network is not homogeneous (x_0/r_0 is constant), there is a difference between the powers flow in the real (natural) case and in the optimal case.

In design and operation process, in order to increase the voltage levels in networks buses and to reduce the active power and energy losses which appear in HV distribution networks elements, a series of constructive, technological and operation measures can be adopted, changing the real power flow closer to the optimal power flow (Neagu *et al*., 2012).

In this paper, we present a solution where for active and reactive power flow optimization the booster transformer is placed in a real HV distribution network. In this context, by using voltage magnitude regulation, the reactive power flows can be controlled. However, phase angle regulation can also be used if the active power flows are to be controlled (Jerbić, 2012).

2. Power Flow Optimization in HV Distribution Networks

Power flow analysis is the mostly used solution in power system operation, planning and management. In HV electricity distribution networks, busses voltage levels and branch power flows are interdependent. Ones can be determined if others are known. To solve the steady-state problem, bus power injections and branch power flow can be used. For real studies, the load flow algorithms need load and voltage data for all network buses (Yan *et al*., 2009).

In Fig. 1 a HV distribution network in a looped configuration with (n + + 1) lines that supplies n consumers is considered. The aim is to determine the power flows that ensure minimum active power losses through Joule effect. The power losses vary with the network configuration and compensation level. They are associated with the resistive elements of lines and of HV/MV transformers. Considering for the loads a constant current model, the MV/LV transformers losses not varying with current and the insulation losses of lines and capacitors can be neglected (Neagu *et al*., 2009).

Adopting a constant voltage in the HV distribution network, equal with the nominal one ($U = U_n$), the expression of power losses through Joule effect can be determined, depending on the active and reactive power flows. By expressing all active and reactive powers depending on the first feeder powers

(P_1, Q_1), and those from every network bus ($P_k^{'}$ and $Q_k^{'}, k=\overline{1,n}$), the active power losses expression (ΔP) depends only on P_1 and Q_1.

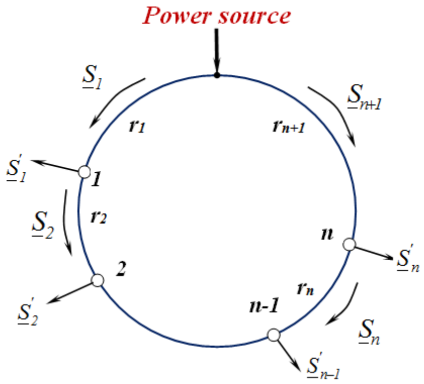

Fig. 1 – The single-phase HV distribution network in looped configuration.

Annulling the partial derivative of the active power loss reported to P_1 and Q_1 ($\partial\Delta P/\partial P_1 = 0$, $\partial\Delta Q/\partial Q_1 = 0$), the optimal (abbreviation, opt) power flows in the first network feeder, $P_{1\text{opt}}$ and $Q_{1\text{opt}}$, presents the following forms:

$$P_{1\text{opt}} = \frac{P_1^{'}\left(r_2+\ldots+r_{n+1}\right)+P_2^{'}\left(r_3+\ldots+r_{n+1}\right)+\ldots+P_n^{'}r_{n+1}}{\sum\limits_{k=1}^{n+1} r_k},$$
$$Q_{1\text{opt}} = \frac{Q_1^{'}\left(r_2+\ldots+r_{n+1}\right)+Q_2^{'}\left(r_3+\ldots+r_{n+1}\right)+\ldots+Q_n^{'}r_{n+1}}{\sum\limits_{k=1}^{n+1} r_k}, \tag{1}$$

where: r_k, $k=\overline{1,n+1}$ are the resistances for the n + 1 network feeders; $P_k^{'}$ and $Q_k^{'}, k=\overline{1,n}$: the active and reactive powers in each HV distribution network bus.

Expressions (1) show that in a looped network the active power losses present a minimum value when active and reactive powers flow are established only with the resistance of every network section. In fact, in alternative current circuits, this flow depends on the impedances of every network section. In this context, in real cases (superscript, real) the active and reactive power flow (P_1^{real} and Q_1^{real}), for first network section, is the following:

$$\underline{S}_1^{\text{real}} = P_1^{\text{real}} + \text{j}Q_1^{\text{real}} = \frac{\underline{S}_1^{'}\left(\underline{z}_2+\ldots+\underline{z}_{n+1}\right)+\underline{S}_2^{'}\left(\underline{z}_3+\ldots+\underline{z}_{n+1}\right)+\ldots+\underline{S}_n^{'}\underline{z}_{n+1}}{\underline{z}_1+\underline{z}_2+\ldots+\underline{z}_{n+1}}, \tag{2}$$

where: z_k represent the (n + 1) network section impedances.

Comparing expressions (1) with (2), can easily observe that the power flow in the real case is identically with the optimal one only if the x_0/r_0 ratio is constant for all network sections (homogeneous network). This criterion is not always satisfied for all electricity transmission and distribution networks.

The significant non-homogeneities exist in looped networks with electric lines at different voltages, connected through high power autotransformers or transformers. The transformers reactance is from 10 to 30 times higher than their resistance, the same ratio for lines being between 1.5 and 3. In these networks, with much non-homogeneity, there is a difference between the powers flow in the real case and in the optimal one, the active power losses being significantly higher in the first case.

In public non-homogeneous distribution networks that operate in looped configuration, the power flow optimization, changing it in the real case closer to the optimal one, can be achieved by following methods (Neagu *et al.*, 2009):

1º Optimally un-loop of the network configuration.

2º Application of supplementary voltage (in phase and quadrature) using a booster transformer.

3º According of electrical lines with capacitor banks through so-called longitudinal compensation.

3. Voltage Regulation Using Booster Transformer

The active and reactive power flows are unevenly distributed in non-homogeneous looped networks leading to high active and reactive powers losses and voltage drops in the network buses (Eremia *et al.*, 2006).

The active and reactive power flows are unevenly distributed in non-homogeneous looped networks leading to high active and reactive powers losses and voltage drops in the network buses (Eremia *et al.*, 2006).

According to some countries regulations, the voltage magnitudes in steady state can vary between 93% and 105% of system nominal voltage. There might be yet another cost for the distribution concessionaire, when there are voltage drops over 4%, beyond the costs with active power losses. The imposition of these limits forces the concessionaires to raise the quality of service to their customers. But, to fulfil all these regulations, a detailed study of voltage correction alternatives must be carried out for the result to be effective and inexpensive (Belivanis *et al.*, 2010).

One of the efficient methods to losses reduction and voltage level improvement in non-homogeneous looped network buses consist in application of supplementary voltages, in phase and quadrature. This method allows the change of power flows in non-homogeneous looped networks in real case, getting it closer to optimal one. This solution can be realized using phase shifting transformers (PSTs) or quadrature boosters transformers (QBTs). This is useful option for controlling power flow over HV distribution lines, because it offer the possibility of flexibly increasing utilization of network thermal capacity under a variety of different conditions, such as to use the available network capacity in a 'smart' way (Belivanis *et al.*, 2010). Both the magnitude and direction of power flow can be controlled by varying the phase shift of PST (Reddy *et al.*, 2012).

The QBTs is another PST type where the injected voltage phasor is shifted by a constant angle with respect to the input voltage vector. Different types of QBT enable different angles. The QBT controllable parameter is the magnitude value of the injected voltage (Wirth *et al.*, 2000). Also, according to Fig. 2, the secondary winding of the QBT is connected in series with a line from the looped network, and the primary winding is supplied from the adjustable transformer (TR) or autotransformer (ATR). In this way, a regulation range between 10% and 15% from the nominal voltage can be assured. As regards the power losses on the whole HV distribution network, these are approximate with 0.5% of the power flow from the controlled line.

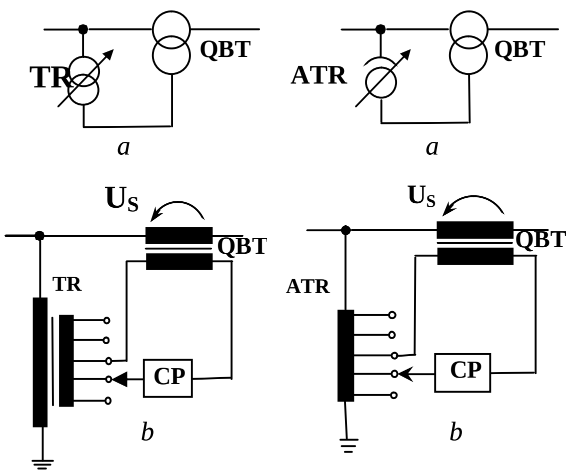

Fig. 2 – Basic diagram of the QBTs: *a* – online diagram; *b* – basic diagram.

The voltage level at each load connection point is one of the most important parameters for the quality of supply and technical regulations or specific contracts define the allowed voltage range that bounds the maximum permitted variation of every bus-bar voltage (Aziz *et al.*, 2011). By using connections between the QBTs and the main transformer or autotransformer, the units of this type can introduce a supplementary voltage in quadrature, defining so called *transversal adjustment control*, according with Fig. 3.

The aforementioned case knows from the specialised literature under the *static phase changer* name. With a restricted operating range, the *transversal adjustment control* is used in correlation with the *longitudinal adjustment control*, when the supplementary voltage in the looped network is in phase with the voltage, also defining so called *long-transversal adjustment control* (Neagu *et al.*, 2009). For additional voltages introduction in HV distribution networks, double induction regulator composed by two electrical machines with the rotors directly coupled (to cancelled their couples) can be used. The rotors windings are supplied at power network voltage and the stator windings are on series mounted on the network, according to Fig. 4.

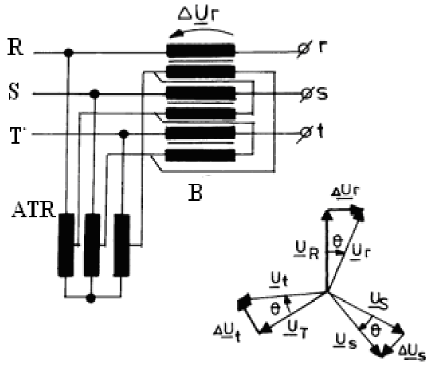

Fig. 3 – Three-phase and vector diagram for transversal adjustment control.

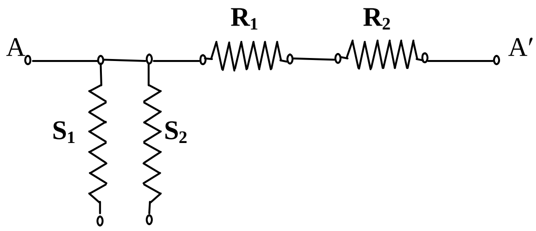

Fig. 4 – Basic diagram for the two inductions regulator usage.

By adopting some adequate connections between the stator windings, a variable voltage can be obtain, in phase and quadrature with power network voltage. To illustrate the effect of supplementary voltages application, the non-homogeneous looped network from Fig. 5 is considered. As seen, at section 1-2 a QBT is connected. The total impedance of the loop is $\underline{Z}_{\Sigma} = R_{\Sigma} + \mathrm{j}X_{\Sigma}$ and the voltage phase in the supplying point *1* is $\underline{U}_1 = U_1\mathrm{e}^{\mathrm{j}0}$.

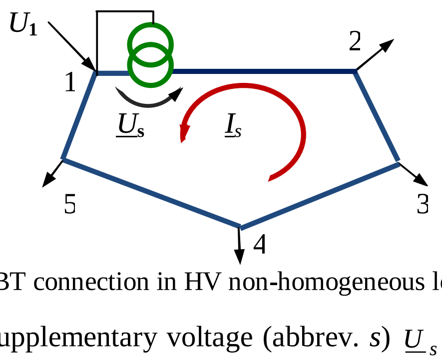

Fig. 5 – The QBT connection in HV non-homogeneous looped network.

Applying a supplementary voltage (abbrev. *s*) $\underline{U}_s = U_{sp} + \mathrm{j}U_{sq}$ (where U_{sp} is supplementary voltage in phase and U_{sq} in quadrature) in the loop appears an additional current, $\underline{I}_s = \underline{U}_s / \underline{Z}_\Sigma$, and additional power flow ($\underline{S}_s$):

$$\underline{S}_s = \underline{U}_1 \underline{I}_s^* = P_s + \mathrm{j} Q_s \tag{3}$$

The expressions for active and reactive supplementary power flow, is:

$$\begin{aligned} P_s &= \frac{U_1 \left(R_\Sigma U_{sp} + X_\Sigma U_{sq} \right)}{Z_\Sigma^2}, \\ Q_s &= \frac{U_1 \left(X_\Sigma U_{sp} - R_\Sigma U_{sq} \right)}{Z_\Sigma^2}. \end{aligned} \tag{4}$$

Analyzing expressions (3) and (4) one can observe the folloing aspects:

a) when $R_\Sigma << X_\Sigma$, the term U_{sp} modifies, especially, the reactive power flow and U_{sq} modifies, especially, the active power flow;

b) when $R_\Sigma >> X_\Sigma$, the term U_{sp} modifies, especially, the active power flow and U_{sq}, modifies the reactive power flow.

Taking into account the aim of the paper (power flow optimization for active power losses minimization and voltage levels improvement) the supplementary voltages which will be introduced are determined starting from the difference between the apparent power flow in the real and optimal case. Solving the linear system given by eqs. (4), the two supplementary voltages (U_{sp} and U_{sq}) are computed.

4. Case Example. Results and Discussion

To exemplify the above described power flow optimization method (including active power losses reduction and voltage level improvement in network buses to which are connected the 110/20 kV stations), a real case with a non-homogeneous looped HV distribution network, is considered.

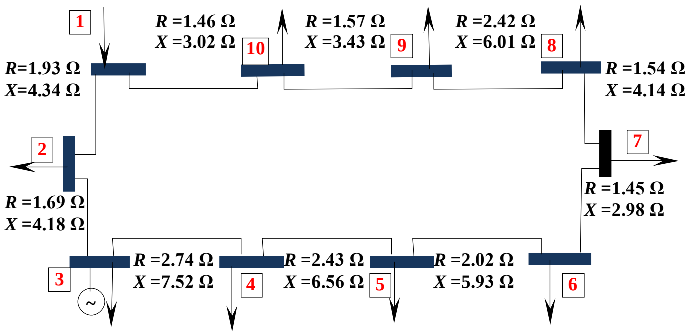

Fig. 6 – Online diagram of the HV distribution network.

The online diagram of the analyzed network is presented in Fig. 6. It should be noted that the QBT is connected between bus 1 and 2 of the network.

The parameters (resistance and reactance) and topology characteristics of the all HV distribution network sections are shown in Fig. 6.

In Table 1 are presented the loads supplied to the step-down transformer station connected in the repartition network, for peak and goal load.

Table 1
Active Power and Power Factor in HV Distribution Network Node at Peak and Goal Load

Bus No.	P_{min}^{C} MW	P_{max}^{C} MW	P_{min}^{G} MW	P_{max}^{G} MW	$\cos\varphi_{min}$	$\cos\varphi_{max}$
2	12	28	–	–	0.85	0.89
3	16	36	25	60	0.86	0.88
4	24	42	–	–	0.84	0.87
5	18	27	–	–	0.84	0.88
6	14	24	–	–	0.86	0.88
7	17	32	–	–	0.85	0.88
8	10	19	–	–	0.86	0.89
9	14	25	–	–	0.85	0.87
10	18	20	–	–	0.85	0.87

For the computation of the continuous rating of the analysed network a software application based on Newton-Raphson method was used, and the first bus being considered slack node with 118 kV at peak load and 116 kV at minimum load. In this way, it had been determined the *real* and *optimal* power flow, at the maximum and minimum load. In Table 2 and 3 the power flow (real or economic case) on sections at peak and goal load, are shortly presented. Also, in Figs. 7 and 8 are shown the voltage level in all 110 kV network buses for the two considered approaches (real or economic case), at peak and goal load.

Table 2
Active and Reactive Power Flow in HV Distribution Network at Peak Load

Bus No.	Bus i	Bus j	Real case				Optimal case			
			P_{ij} MW	Q_{ij} MVAr	P_{ji} MW	Q_{ji} MVAr	P_{ij} MW	Q_{ij} MVAr	P_{ji} MW	Q_{ji} MVAr
1	1	2	82.03	80.7	53.22	50.24	85.117	83.84	44.03	44.03
2	2	3	52.7	52.18	35.9	34.61	55.84	55.34	29.69	29.62
3	3	4	76.18	74.43	47.56	42.78	79.34	77.68	42.64	42.64
4	4	5	32.44	32.14	18.98	18.18	35.69	35.38	18.84	18.84
5	5	6	5.14	5.13	3.61	3.59	8.38	8.37	4.27	4.27
6	6	7	18.86	18.92	9.35	9.47	15.63	15.66	8.67	8.67
7	7	8	50.92	51.37	26.74	27.96	47.66	48.02	25.94	25.94
8	8	9	70.37	71.7	37.69	40.98	67.02	68.09	35.67	35.67
9	9	10	96.7	98.26	55.15	58.56	93.09	94.41	49.93	49.93
10	1	10	118.26	120.4	69.89	74.23	114.41	116.2	61.16	61.16

Considering all network non-homogeneities, there is a significant difference between the apparent power flow in the real and optimal case:

a) $\underline{\Delta S}^{v} = \underline{S}_{s}^{v} = 4.138 + \mathrm{j}13.07$ [MW, MVAr] at peak load (abbrev. *v*);

b) $\underline{\Delta S}^{g} = \underline{S}_{s}^{g} = 2.22 + \mathrm{j}5.05$ [MW, MVAr] at goal load (abbrev. *g*).

Table 3

Active and Reactive Power Flow in HV Distribution Network at Goal Load

Bus No.	Bus i	Bus j	Real case				Optimal case			
			P_{ij} MW	Q_{ij} MVAr	P_{ji} MW	Q_{ji} MVAr	P_{ij} MW	Q_{ij} MVAr	P_{ji} MW	Q_{ji} MVAr
1	1	2	47.47	46.99	33.57	32.48	49.45	48.97	30.39	30.39
2	2	3	34.99	34.75	25.04	24.45	36.97	36.72	22.95	22.95
3	3	4	43.75	43.14	29.78	28.12	45.72	45.12	28.29	28.29
4	4	5	19.14	19.04	12.64	12.36	21.12	21.01	12.81	12.81
5	5	6	1.04	1.04	0.74	0.74	3.01	3.006	1.2	1.2
6	6	7	12.96	12.99	7.55	7.61	10.99	11.01	7.09	7.09
7	7	8	29.99	30.15	18.15	18.58	28.01	28.15	17.63	17.63
8	8	9	40.15	40.59	24.51	25.61	38.15	38.52	23.56	23.56
9	9	10	54.59	55.11	34.29	35.43	52.52	52.98	32.24	32.24
10	1	10	73.11	73.96	46.59	48.45	70.97	71.74	43.4	43.4

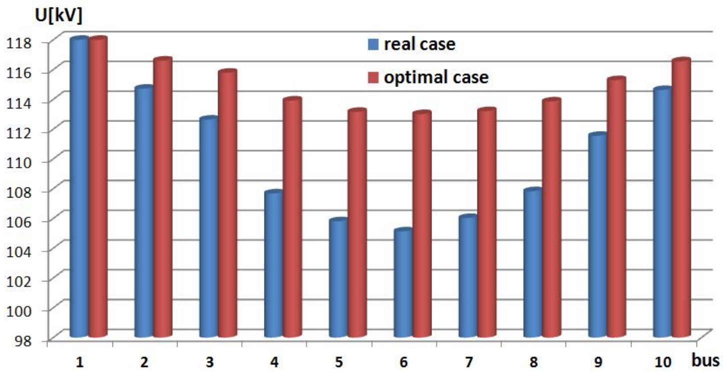

Fig. 7 – The voltage levels, in the realand optimal case at peak load.

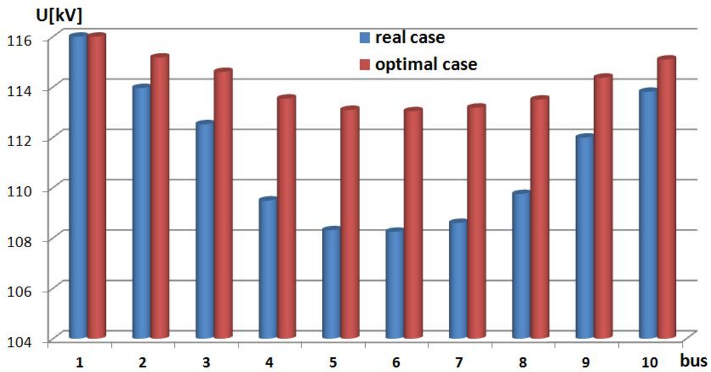

Fig. 8 – The voltage levels, in the real and optimal case at goal load.

To bring the HV repartition network analyzed to the optimal operating state, a supplementary voltage, ($\underline{U}_s^v = 6.01 - \mathrm{j}0.445$ [kV] for maximum or peak load and $\underline{U}_s^g = 2.383 - \mathrm{j}0.114$ [kV] for goal load), must be applied through booster transformer, emplaced on the lines between 1 and 2 buses of the repartition network in looped configuration.

4. Conclusions

The power flow optimization in HV distribution networks in looped configuration by application of supplementary voltages (using quadrature booster transformers), is one of the most efficient methods for power losses reduction and voltage level improvement in the non-homogeneous networks of buses. In this paper, a new approach for power flow optimization and voltage level improvement is proposed. For the analyzed HV distribution networks, the reduction of power losses are 3.686 MW at peak load and 0.138 MW at goal load. The voltage levels were considerable improved according to Figs. 7 and 8.

The application of this method in operation require the existence of a regulation assembly with QBT emplaced on the power line from the non-homogeneous looped network which has to admit the introduction of supplementary voltage in phase and quadrature, adjustable voltages respectively.

When the real steady-state from the analysed HV distribution network admit, can be made the optimal reconfiguration and the network operate in radial configuration (in this case, the section which can be disconnected are between the nodes 5 and 6). In the analyzed network case, for the studied cases, peak and goal load, the consumption separation on the two bars systems can be realized in the power stations no. 6. This solution is disadvantageous because the supplying security level with electricity of the consumers is reduced.

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OPTIMIZAREA CIRCULAȚIILOR DE PUTERI UTILIZÂND TRANSFORMATOARE BOOSTER ÎN REȚELELE DE DISTRIBUȚIE DE ÎNALTĂ TENSIUNE

(Rezumat)

În țara noastră, rețelele electrice de distribuție de înaltă tensiune funcționează în configurație radială sau buclată şi alimentează cu energie electrică stațiile de transformare coborâtoare de 110 kV/MT. Prin intermediul acestor stații sunt alimentați cu energie electrică un număr mare de consumatori casnici şi terțiari din mediul urban. În cadrul lucrării este propusă o abordare pentru optimizarea circulațiilor de puteri active şi reactive. Prin conectarea transformatoarelor booster în rețelele reale de distribuție de înaltă tensiune (110 kV), pierderile de putere activă şi reactivă pot fi reduse iar nivelul tensiunilor poate fi îmbunătățit. În finalul lucrării, sunt prezentate principalele rezultate, discuții şi concluzii.