# Optimization of Power Distribution Networks in Megacities

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**Abstract**. The study deals with the problem of city electrical networks optimization in big towns and megacities to increase electrical energy quality and decrease real and active power losses in the networks as well as in domestic consumers. The optimization is carried out according to the location selection and separate reactive power source in 10 kW networks of Swarm Intelligence algorithms, in particular, of Particle Swarm one. The problem solution based on Particle Swarm algorithm is determined by variables being discrete quantities and, in addition, there are several local minimums (troughs) to be available for a global minimum to be found. It is proved that the city power supply system optimization is carried out by the additional reactive power source to be installed at consumers location reducing reactive power flow, thereby, ensuring increase of power supply system quality and decrease of power losses in city networks.

## 1. Introduction

Optimization problems of city electric networks include the definition of steady-state electrical network mode where technical constraints on electrical energy quality have been sustained. Three basic problems of optimization have been highlighted in the distribution networks where each problem requires its own optimization method: selection of optimal allocation and source power of reactive power, optimization of transformation coefficients and selection of optimal points of circuits' interruption. The optimization takes into consideration the voltage deviation constraints in all nodes including load nodes with no controlling means available per reactive power of sources generated and per currents controlled within the lines [1–2].

Reactive power optimization is defined as the best location of installation and selection of compensating units power value (CU). CU comprises of a capacitor bank, electric switchgear, protection and controlling means.

With partial or complete reactive power compensation consumed by current-using equipments the current and the voltage drop in power lines is decreased and at the same time real power losses are also decreased in the network.

## 2. Statement of Problem

The function analysis of power supply systems in big cities and megacities shows that their essential part consists of distribution networks of 10–35 kW, and in many developing countries the networks have 20 kW voltages [3]. Significant influence on sustainable development of city electrical networks has the effectiveness increase and the quality of city power supply system functioning. Thus, the urban

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dweller's quality life index is determined by three factors: ecological environment, education and health care services and technical support comfort of vital communication functions including quality and accessibility of electrical and thermal energy. The vital importance of sustainable urban development is power consumption increasing of not only real but active power, which is necessary for domestic electrical appliances to be operational. The operating principal is based on magnets fields' applying. Reactive power consumption in urban area is conditioned by three factors:

- Rapid growth of urban population and urban settlements' area.
- Increasing number of electrical appliances (with electrical engines) used by population, in particular, washing machines, fridges, air-conditioners, dishwashers, vacuum-cleaners, fans, pumps and others.
- Significant increase of city Power Transmission Lines (PTL) length corresponds to the urban expansion area what increases real and reactive power losses while transporting electrical power at a distance.

This problem, in its turn, is resolved by two necessary solutions, in particular, selection of optimal nodes of compensating units allocation with minimal of the reduced costs and selection of optimal values of reactive power in operating condition including minimal losses. In this case, the CU's installed capacity takes the form of a constraint.

The attempt of taking two decisions is undertaken in this study with their further combination made. The first stage considers the calculation of steady-state mode with parameters set in the network and loads. The second one is used by the Swarm Intelligence algorithm where at each stage the access towards the objective function value is implemented being defined by the first problem. Genetic algorithms do not guarantee much better solution to be found but they usually allow getting "fast enough" of "reasonable" problem solution. It is the composition of these two problems solution which introduces the basic research novelty of the study presented [4–5].

## 3. Mathematical Model of Problem

Currently, in order to solve problems related to sustainable development of big cities and megacities, the more attention is paid to the energy savings and to production processes efficiency increasing. Thus, the technical and economic performance of city power grid enterprises has been significantly improved being resulted in the tariff reduction of electrical power and other energy carriers. It, in its turn, reduces harmful emissions produced by power stations and, thereby, the quality of ecological environment is improved. Power losses decrease contributing to the tariff reduction improves economic viability of urban dwellers and reduces the poverty alleviation countrywide.

To decrease electric power losses the following methods are available:

- Design and application of energy savings technologies;
- Allocation optimization and power sources selection of reactive energy;
- Smart grid design using new principles, innovations and process control.

The selection of mathematical model to solve the optimization problem of power supply for the cities to be sustainably developed is defined by the fact that the problem has discrete variables and can contain several local minimums out of which the selection of the global one is crucial. Widely applied gradient methods are not suitable for this task as they require function derivation. This requirement is not observed in this task, moreover, for big cities with big quantity of adjunctions the system of equations has high dimension and under sustainable city development the "curse of dimensionality" is being increased in quadratic degree. Due to this, more effective method of discrete optimization was chosen in this study with the possibility of defining of global minimum – the Swarm Intelligence method.

The aim of optimization is the minimization for real power losses and for CU costs. Thus, power factor tgφ for grids with 10 kW is limited by 0.4 variables. As the result, the optimization problem is formulated:

$$W(Q) = Z_{\Delta P}(Q) + Z_{CU}(Q) \to \min$$

where $Z_{\Delta P}$ is financial losses of real power , $Z_{CU}$ is financial costs provided to CU installation and defined as:

$$Z_{\Delta P} = C_p \cdot \tau \cdot \Delta P,$$

with the following constraints: $0 \le \mathrm{tg}\varphi \le 0,4$

where $Q$ is a CU power vector;

$Q_i$ is CU power in n-node (if $Q_{maxi} = 0$, CU is not put down in n-node);

$n$ – is a number of nodes which can CUs can be installed in;

$\tau$ – time period/interval of system operation considered per hour/annum corresponds to 8760 hours;

$\Delta P_\Sigma$ – is total active power losses in the network;

In order to solve the problem the fragment of megacity's city distribution network has been selected consisting of 36 – nodes and 48 – arms (Figure 1).

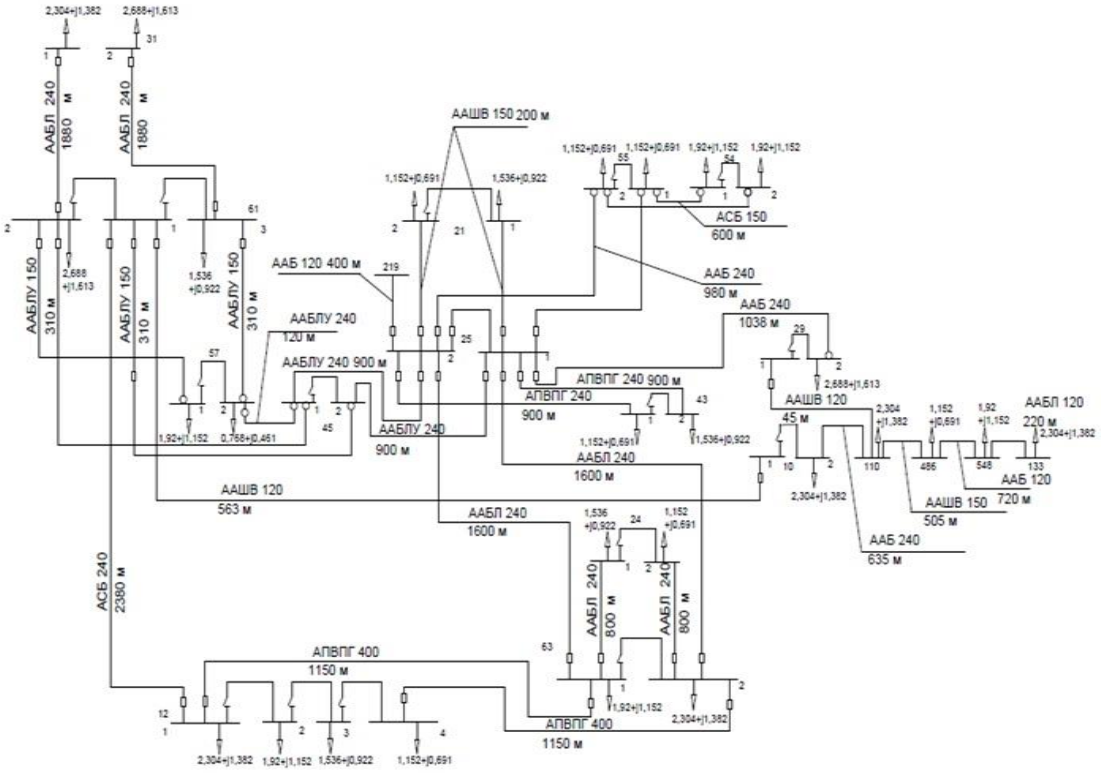



**Figure 1**. Fragment of Electric Distribution Network

## 4. Particle Swarm Algorithm

The following regulations have been introduced:

- Particles existing in the world where time is discrete;
- Particles estimate their position by means of fitness-function;
- Each particle knows its position in the area where it has found the most amount of food (its best position);
- Each particle knows its position in the area where the most amount of food among all positions is and where all particles have been available (the best common position);
- Particles strive to take the best positions where they have been already themselves and occupy the best common position;

- Particles, at random, change their speed in such way that the described tendency defines only average motion of particles;
- Particles have inertia and that is why their speed is dependable each time on the previous time speed;
- Particles cannot abandon the limited searching area.

The main idea of the method is in particles movement in the space of solutions. Let the problem of finding the minimum (maximum) of a function $f(X)$ is solved, where X is a vector of different variables that can take values from some area of D. Then each particle at any time is specified by value of X parameters from D area (points data in solution space) and value of optimized function $f(X)$ (being attractive to this point). In this case, the particle ″remembers″ the best point being in the solution space and strives to come back but it should obey the law of inertia tending towards some stochastic variation of movement direction. Nevertheless, these rules are not enough to be transformed to the system as the links among elements have not been set. As a link, so called, general memory is used due to which each particle is aware of the best point coordinates being among all ones where any particle has been earlier. Finally, it is striving to be engaged in the best position among all the particles available being influenced by the particle movement among other particles, inertia, and random deviations [6–7].

The algorithm is completed at reaching of certain allocated number of iterations either with reaching of the satisfactory solution or upon completion of the operation after certain period of time. Consequently, algorithm can be written as follows:

1. To randomly distribute particles in the solution area and set zero initial speeds.
2. Optimized function values with each particle renewal if local and global best solutions are required.
3. To calculate new values of speeds per each particle.
4. To calculate new coordinates of particles.
5. If the termination condition is satisfied, the algorithm should be completed: otherwise, step 2 needs to be taken.

The result of algorithm operation is the best global solution.

According to the formula, the Particle Swarm algorithm is $PSO = \{S, M, A, P, I, O\}$.

1. Set of agents (particles) $S = \{s_1, s_2, \ldots, s_{|S|}\}$, $|S|$ is a number of particles . On $j$-iteration i particle is specified by the state of $s_{ij} = \{X_{ij}, V_{ij}, X^{best}_{ij}\}$, where $X_{ij}=\{x^1_{ij}, x^2_{ij}, \ldots, x^l_{ij}\}$ is a vector of variable parameters (particle's position), $V_{ij}=\{v^1_{ij}, v^2_{ij}, \ldots, v^l_{ij}\}$ – is a vector of particle speeds, $X^{best}_{ij}=\{b^1_{ij}, b^2_{ij}, \ldots, b^l_{ij}\}$ is better in value of fitness-function of the particle position among all the positions which was taken by the algorithm operation from the 1st to $j$ iterations, $l$ is a number of variable parameters.

2. The vector $M = X^{best}j$ is the best value of variable parameters vectors which has been obtained among all the particles from the 1st to $j$-iteration of algorithm. This vector provides the indirect experience exchange among the particles.

3. A algorithm describes the Particle Swarm functioning. There are different modifications of this algorithm. Further, the basic algorithm description is provided.

3.1. Generation of initial positions and speeds are (j = 1):

$$X_{i1} = rand(G(X)), i = 1, \ldots, |S|,$$

where r and $(G(X))$ – are a vector of equally distributed random values meeting the constraints onto the searching area;

$$V_{i1} = rand(-V_{\max}, V_{\max}), i = 1, \ldots, |S|,$$

where r and $(-V_{max}, V_{max})$ – are a vector of equally distributed random values in the range of $(-V_{max}, V_{max})$.

$$X_{i1}^{best} = X_{ij}, i = 1,...,|S|.$$

The best position is selected on a random basis (while calculating fitness-functions the real best position will be defined):

$$X_{1}^{best} = X_{11}.$$

3.2. Fitness-function calculation and definition of the best position are as follow:

$$X_{ij}^{best} = X_{ij}, \phi(X_{ij}^{best}) < \phi(X_{ij}), i = 1,...,|S|,$$

$$X_{j}^{best} = X_{ij}, \phi(X_{j}^{best}) < \phi(X_{ij}), i = 1,...,|S|.$$

The calculation of $\varphi(X) = f(X)$ takes place in the external environment through data exchange with feedback of ($I_{oc}$ ,$O_{oc}$).

3.3 Particles' movement:

$$V_{ij+1} = V_{ij}\omega + \alpha_1\left(X_{ij}^{best} - X_{ij}\right)rnd_1 + \\ +\alpha_2\left(M - X_{ij}\right)rnd_2,\ i = 1,\ldots,|S|,$$

$$V_{ij+1} = \begin{cases} V_{ij+1}, -V_{\max} \le V_{ij+1} \le V_{\max} \\ -V_{\max}, V_{ij+1} \le -V_{\max} \\ V_{\max}, V_{ij+1} \ge V_{\max} \end{cases}, i = 1,\ldots,|S|,$$

$$X_{ij+1} = \begin{cases} X_{ij} + V_{ij+1}, G(X_{ij} + V_{ij+1}) = 1 \\ X_{ij}, G(X_{ij} + V_{ij+1}) = 0 \end{cases}, i = 1,\ldots,|S|,$$

where $rnd_1$ and $rnd_2$ are random numbers equally distributed in the interval [0,1), $G(X)$ is used as the predicate showing whether the $X$ is belonged to the $D$ area of possible values.

3.4. If on j iteration the termination condition is fulfilled, the value $X_{final}^{best} = X_j^{best}$ is supplied to the output $O_1$. Otherwise, the transition towards the iteration 2 is taken place.

4. The vector $P = \{\alpha 1, \alpha 2, \omega\}$ are coefficients of $A$ algorithm which are used in the formula and correspondingly influences the particles' movement in searching area. Correspondingly, $\alpha_1$ and $\alpha_2$ coefficients define the influence the agent's individual and group experience. The coefficient ω specifies the inertial properties of particles.

5. The $I$ and $O$ identifiers, which have described earlier the input and output of swarm, are not dependent on the Swarm Intelligence algorithm implementation.

## 5. Electrical Network Optimization

The optimization is carried out by means of algorithm based on the Swarm Intelligence, the optimal distribution of reactive power sources is obtained and the reactive power value of the selected nodes is obtained as well [8]. The parameters are set for the optimization to be required: the cost of electricity for 1 kW/hour is $\beta$ = 2.6 rub, the cost for 1 kVAr of the installed capacity is $Q$ = 550 rub. The obtained values of the reactive power are tabulated in 1. Total losses of real power are ΔP = 0.888 MW. The required value of the compensated reactive power is $Q$ = 7.886 MVAr.

**Table 1.** Reactive distribution and value

| Node | Q MVAr |
|---|---|
| 133 | 1.244 |
| 241 | 0.830 |
| 242 | 0.622 |
| 571 | 1.037 |
| 572 | 0.264 |
| 541 | 0 |
| 542 | 0 |
| 291 | 0 |
| 121 | 1.194 |
| 311 | 1.244 |
| 312 | 1.452 |

## 6. Operational Task for Electrical Network Optimization

The distinctive feature of project problem being considered in the sub-section 3.3 presents the constraints being imposed on CU, in particular, on the value of the installed capacity [9]. The constraints set have been presented in the Table 2. If the value is $Q_{cu\ p}<Q_{max.est}$, the optimization program in the assigned node sets up the value being equal to the reactive power $Q_{cu}=Q_{cu\ p}$, otherwise with $Q_{cu}>Q_{max.est}$ towards the assigned node, the maximum reactive power is set up equaling to $Q_{cu}=Q_{max.est}$.

**Table 2**. Maximum installed reactive powers

| Node | $Q_{cu\ p}$, MVAr | $Q_{max.est}$, MVAr |
|---|---|---|
| 133 | 1.244 | 1.250 |
| 241 | 0.830 | 0.850 |
| 242 | 0.622 | 0.600 |
| 571 | 1,037 | 1.000 |
| 572 | 0.264 | 0.400 |
| 541 | 0 | 0 |
| 542 | 0 | 0.700 |
| 291 | 0 | 0 |
| 121 | 1.194 | 1.200 |
| 311 | 1.244 | 1.250 |
| 312 | 1.452 | 1.450 |

Real $tg\varphi_{nat}$ of load and $tg\varphi_{opt}$ after optimization are calculated

$$tg\phi_{nat} = \frac{Q_n}{P_n},$$

After optimization:

$$tg\phi_{opt} = \frac{Q_n - Q_{cu}}{P_n},$$

For example, for the node 133, where $P_n$ = 2.314 MW, $Q_n$ = 1.382 MVAr, $Q_{cu}$ = 1.244 MVAr,

$$tg\phi_{nat} = \frac{1.382}{2.304} = 0.59,$$

$$tg\phi_{opt} = \frac{1.382 - 1.244}{2.304} = 0.059$$

The other calculations have been presented in Table 3. Total losses of active power are $\Delta P$ = 0.883 MW. The required value of the compensated reactive power is $Q$ = 8.667 MVAr.

Thus, in the conditions of real maintenance and presented constraints per compensated devices, the real power total losses increase by 0.001 MW, i.e., by 1 kW. In this case, the power of mounted batteries is increased with rounding of numbers of their power towards down by 106 κVAr. Thus, the optimization results confirm the correctness of the problem solution in the project formulation.

**Table 3**. Optimization results by nodes

| Node | $P^n$, MW | $Q_n$, MVAr | $Q_{cu}$, MVAr | $tg\varphi_{nat}$, r.u | $tg\varphi_{opt}$, r.u |
|---|---|---|---|---|---|
| 133 | 2.304 | 1.382 | 1.244 | 0.59 | 0.05 |
| 241 | 1.536 | 0.922 | 0.830 | 0.6 | 0.04 |
| 242 | 1.152 | 0.691 | 0.600 | 0.59 | 0.08 |
| 571 | 1.92 | 1.152 | 1.000 | 0.6 | 0.08 |
| 572 | 0.768 | 0.461 | 0.400 | 0.6 | 0.08 |
| 541 | 1.92 | 1.152 | 0 | 0.6 | 0.6 |
| 542 | 1.92 | 1.152 | 0.700 | 0.6 | 0.23 |
| 291 | 0 | 0 | 0 | 0 | 0 |
| 121 | 2.304 | 1.382 | 1.200 | 0.59 | 0.08 |
| 311 | 2.304 | 1.382 | 1.250 | 0.59 | 0.08 |
| 312 | 2.688 | 1.613 | 1.450 | 0.6 | 0.06 |

## 7. Conclusion

1. The sustainable development of cities and megacities, by all means, requires a new approach in the task of increasing technical and economic performance of city power grid enterprises and power supply system at large. The quality of city power supply system functioning must correspond to the improvement of technical comfort of urban habitat. Due to it, the city development is accompanied by significant changes of domestic electrical appliances' composition and requirement towards the quality of electrical power being necessary for their operation.

2. The study shows that one of the abovementioned conditions for technical development becomes an innovation task for selection of optimal placement reactive power compensating units and further optimization exploitation of values selection providing the reactive power into the network which controls the city electrical network modes. To reduce power losses in power networks and to meet the quality criteria of electrical power on voltage deviation the concrete values of reactive power source values are being optimally selected within daily time interval.

3. The optimization was carried out by Swarm Intelligence algorithm as the problem had discrete functions and it was necessary to find global minimum of target function.

It is proved that as the result of optimization the best variant on minimum of losses requires CU' installation with power of Q = 8.773 MVAr. Total real power losses are reduced from 1.063 to 0.882 MW making 7.7 %. The payback period of this exercise makes 1.6 years. Thus, the reactive power compensation in city power networks is quite efficient, cost effective and significantly improves technical and economic performance of electrical grid enterprises and promotes the sustainable development of cities.

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