Dimensioning appropriate technical and economic parameters of elements in urban distribution power nets based on discrete fast marching method

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Abstract. The main purpose of the research is to develop techniques for defining the best technical and economic trajectories of cables in urban power systems. The proposed algorithms of calculation of the routes for laying cables take into consideration topological, technical and economic features of the cabling. The discrete option of an algorithm Fast marching method is applied as a calculating tool. It has certain advantages compared to other approaches. In particular, this algorithm is cost-effective to compute, therefore, it is not iterative. Trajectories of received laying cables are considered as optimal ones from the point of view of technical and economic criteria. They correspond to the present rules of modern urban development.

1. Introduction
The problem of the best arrangement of elements in operating power nets is one of the main ones. Thus, it is supposed to be solved first when designing. The whole performance of an electrical power system for a long time mostly depends on the right choice of the way the nodes in the distribution power net are located.

A keen interest in this issue among scientists has been observed recently. A great number of publications are dedicated to this subject.

The work of heuristic algorithms is resulted in many papers printed in scientific journals [7, 8, 9, 10].

Using geo-information technologies considerably enlarges researchers’ opportunities in this regard [6].

Continuously increasing consumption of electric power in urban agglomerations, as well as a growing heterogeneity of density of loading is resulted in the need to take into account topological, technical, and economic features of areas for designing engineering systems, including urban nets of power system.

In the urban environment networks power system are mainly performed using electrical cables (EC) departing from the sub-transformers (ST) of 10 (6)/0.4 kV to switchgears.

The density of urban constructions, intensity of underground utilities, other engineering nets as well as high commercial cost of those urban lands make the process of choosing the most effective technical and economic routes more complicated for laying low-voltage nets.
There is a need to bring new approaches when designing the utilities minding various features of a particular region.

In this regard, the authors offer to use the opportunities of geo-information technologies and algorithms of searching the most appropriate routes.

2. Materials and methods

Actually, the problem of defining the most reasonable trajectory is long-standing. Besides, it has also received rather wide coverage in scientific and educational literature lately.

There are a lot of algorithms to find optimal trajectories according to the conditions of the task being solved.

In this paper, the application of the algorithm “Fast marching method” (FMM) is focused on. The use of this method allows considering influence of technical, economic and topological features of the region when determining optimal routes for laying cables.

The FMM algorithm is a part of so-called Level Set Methods, which are applied in different fields of scientific and technical research due to computing speed. They include computer graphics, processing medical images, dynamics of liquids, and others.

This method interprets target function values of the calculated costs as “a potential field” in a spatial domain intended for defining optimal trajectories.

The solutions of Hamilton-Jacobi equation for a formal “potential field” called Eikonal equation allows one to define the least wasteful trajectory between the chosen points in a certain region.

The running of FMM can be imagined as a distribution of the wave front across the dissimilar environment described as “a potential field”.

The wave front G in each point passes through the normal. Speed F in each point of the wave front, generally has different values, but it is always positive.

As it has been noticed before, the movement of each point of the wave front meets Eikonal equation [2]:

\[ 1 = F(x) \left| \nabla T(x) \right|, \]

(1)

\( X \) is a coordinate vector here, dimensionally equals to the considered area, \( F(x) \) is the speed of movement of a wave in this point, and \( T(x) \) is the time of the movement of the wave front from a source to the considered point.

Eikonal equation implies that the module of a gradient \( \left| \nabla T(x) \right| \) is in the inverse proportion to the speed:

\[ \frac{1}{F(x)} = \left| \nabla T(x) \right|. \]

(2)

As each point of the wave front directs to the external normal, that is \( F(x) \geq 0, \forall x \) means that \( T(x) \) in each point has a unique value.

In 1996 J. Sethian considered Eikonal equation (1, 2) for a discrete case and proposed the solution which is the cornerstone of the algorithm used [1].

The formula of Eikonal equation for the discrete 2D space can be shown below:

\[ \max \left( \frac{T - T_1}{\Delta x}, 0 \right)^2 + \max \left( \frac{T - T_2}{\Delta y}, 0 \right)^2 = \frac{1}{F_{i,j}^2}. \]

(3)

The authors assume that \( F(x_j, y_j) > 0 \), (3) so it is possible to present it as follows:

\[ \left( \frac{T - T_1}{\Delta x} \right)^2 + \left( \frac{T - T_2}{\Delta y} \right)^2 = \frac{1}{F_{i,j}^2}. \]

(4)

Equation (4) can be solved by the discrete 2D diversity.
In order to test the performance of the algorithm, the area of urban medium rise housing was chosen which is presented in figure 1 [5]. Figure 1 represents the map of the area covered by sub-transformers. A rhombus marker indicates coordinates of the switchgears, and a star marker points at the proposed location of sub-transformers defined as the topological center of consuming loads [2].

The practical use of the algorithm FMM starts with a creation of the potential field (in terms of the weight map) of the considered area.

In the context of the task reviewed, the weight map represents the image of shades in a grey colour where each of them exactly calculates technical and economic costs of laying a unit length of the cable in this particular point.

Costs of laying a cable within the presented area have different values in different points. Moreover, in certain sites, it is impossible to lay a cable because of some urban construction reasons and the limits connected with regulations for installing power systems [3].

As for the costs of laying a cable, the given area can be shown as in figure 2.

This picture is submitted in a variety of the grey color where the most preferable sites for laying a cable have lighter shades. Sites which are inaccessible for laying a cable are marked as black in colour.

The authors accept coordinates of switchgears as sources or initial points in the algorithm FMM, and process the marked area in turn. Finally, a set of maps images of geodetic distances for each separate load will be received.

Each point on this map contains information on costs of laying a cable from the initial point (the location of switchgears). In this case, lighter sites correspond to points with big expenses required.

Summarizing maps of geodetic distances for each load, let us receive the cumulative matrix of geodetic distances $D_G^t$ which is the weight map for the search algorithm of the optimal trajectory.

Figure 3 illustrates the mentioned approach.
Figure 2. Marking the area covered by the urban sub-transformers 10 (6)/0.4 kV.

The cumulative map of geodesic distances

Figure 3. The cumulative map of geodetic distances

The CMGD minimum point is marked by “a star” in figure 3. Originally, an anticipated location of sub-transformers, for comparison, is marked by “a hexagon”.

For each point of the image of CMGD by means of Sobel filter, one should calculate directions in which the gradient reaches the maximum values in order to define the optimal trajectories of cables.

The Sobel filter represents two matrixes 3x3, one of them defines $x$, that is, a gradient vector projection, the other, accordingly, represents $y$ -projection.
The process of using Sobel filter is an operation of convoluting matrices of the filter with CMGD according to these expressions:

\[
\begin{align*}
grad_x &= \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} \ast D_G^{e_l} \\
grad_y &= \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} \ast D_G^{e_l}
\end{align*}
\]

The projections of gradients are defined for each point of CMGD. The optimal way is calculated iteratively, point by point, according to the expressions below:

\[
\begin{align*}
\text{mod}_i &= \sqrt{\text{grad}_{ix}^2 + \text{grad}_{iy}^2} \\
\alpha_i &= \arctan \left( \frac{\text{grad}_{iy}}{\text{grad}_{ix}} \right) \\
p_{i+1,x} &= p_i + \text{mod}_i \cdot \cos(\alpha_i) \\
p_{i+1,y} &= p_i + \text{mod}_i \cdot \sin(\alpha_i)
\end{align*}
\]

3. Results and discussion
The optimal trajectories for laying cables, which are under consideration, are presented in figure 4.

![Figure 4](image-url)
This method differs from those that use heuristic algorithms. In the given approach, synthesis of classical algorithms of searching optimal trajectories by means of geo-information technologies is applied.

This method is quite intuitive for a research engineer, so one does not have difficulty in geodetic distances mapping.

4. Conclusion
The following outlines are possible to submit as a result of the research.

1. The proposed approach allows finding optimal technical and economic criteria of a trajectory for laying cables in the crowded urban construction conditions.
2. The developed algorithms of searching optimal routes by FMM and using data of geographic information system allow taking into account real local features of places estimated for laying cables.
3. This method has a number of advantages in comparison with widely applied heuristic methods. The operating speed and rather low computing intensity of this approach are also important.
4. It does not seem complicated for designers of urban power systems to use this method.

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