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# Economic Assessment of Distribution Network Reconfiguration and Capacitor Switching

**Tomislav Rajić[1], Branko Stojanović[2*]**

[1]*Elektrotehnički fakultet, Beograd, Serbia*
[2]*Tehnički opitni centar, Beograd, Serbia*

***Corresponding Author:** Branko Stojanović, [2]Tehnički opitni centar, Beograd, Serbia, Email: stojanovic.branko@rocketmail.com*

## ABSTRACT

*This study presents approach to feeder reconfiguration and capacitor settings. The merit of the methods is that they can prove a global or near-global optimum. Optimal reconfiguration and capacitors control allow cost-effective and reliable operation of networks, reducing power losses and flattening voltage profile. Three methods based on SA are presented and compared economically (simultaneous reconfiguration and capacitors switching, reconfiguration and then capacitors switching and eventually capacitors switching and then reconfiguration). Cost-effective analyses conducted on Baran and Wu network is presented and objective function consists of capacitors and losses price while neglecting cost of energy. The programme for checking the connectivity of the power system, with imposed radiality constraint, is enhanced with MATPOWER precise power flow method. The time duration of simultaneous reconfiguration and capacitors switching method is of an hour order and does not depend on the fast manipulation of incoming data files. This advantage makes the method interesting in the planning stage as well as the application in real time.*

*Main contribution of this paper is a novel approach which exploits mostly the following mechanisms: network connectivity checking matrix, Lavorato et al. criterion for imposing radiality constraint and efficient power flow algorithm in MATPOWER environment.*

**Keywords:** *capacitor cost, active power loss, connectivity, radial configuration, simulated annealing.*

## INTRODUCTION

Optimal reconfiguration and capacitors control allow cost-effective and reliable operation of networks, reducing power losses and flattening voltage profile. The single problems of compensation and reconfiguration have been extensively considered in literature. The first has been treated mainly in terms of optimal design, namely trying to find optimal location, the size and type of the capacitor banks to be installed. With regard to the minimum losses operation of radial networks, the reconfiguration problem has been handled in many papers in which both heuristic and mathematical solution methodologies have been proposed. The problem connected to the optimal reconfiguration and compensation so as to get minimum losses operation has been discussed in **[1]** and **[2]** where a Simulated Annealing algorithm (SA) is proposed to solve the present problem.

In this paper novel approach to find the best configuration and the best capacitors setting is given. Three methods based on SA are presented and compared economically (simultaneous reconfiguration and capacitors switching, reconfiguration and then capacitors switching and eventually capacitors switching and then reconfiguration). Cost-effective analysis conducted on Baran and Wu network **[3]** is unique and objective function consists of capacitors and losses price while neglecting cost of energy.

The general capacitor placement problem is a NP-complex combinatorial optimization problem with a non-differentiable objective function (the capacitor cost function is step-like and non-differentiable). NP stays for Non-deterministically in Polynomial-bounded time, and it is used to indicate problems not solvable in a reasonable computation time which is exponentially growing with the number of variables. Capacitors are widely installed in distribution systems for reactive power compensation, to achieve power and energy reduction, voltage regulation and system capacity release. The extent of these benfits depends greatly on how the capacitors are placed on the system. The problem of how to place capacitors on the system so that these benefits are achieved and/or maximized against the cost associated with the capacitors placement is termed the general capacitor placement problem.

A general solution algorithm based on simulated annealing for optimal capacitor placements in distribution systems is proposed and analyzed in **[4, 5]**.

The network reconfiguration requires determination of the best combination of branches, one from each loop, to be switched out so that resulting radial distribution system incurs minimal kW losses. The reconfiguration of network is obtained by changing the status of sectionalizing (normally closed) and tie line (normally open) switches. Since the statuses of the tie switches and sectionalizing switches are binary (open or closed), the solution space is discontinuous. Owing to the discontinuous and discrete nature of the problem, classical techniques are rendered unsuitable and the use of global search techniques is warranted.

Network reconfiguration belongs to "minimum spanning tree" problems (network looks like a spanning tree) known also as NP - combinatorial optimization problems. Algorithm should find minimum loss configuration, system constraints being satisfied.

We seek the jointly optimal switch configuration and capacitor settings that minimize objective function. Cost objective function comprises of value of losses multiplied with 120$/kW penalty factor and cost of capacitors multiplied with factor 0.15 which represents the capacitor price annual interest rate. Other construction of objective function is possible but previously mentioned is presented in the paper. The computational difficulty in achieving this goal is due to the discrete nature of the two problems.

Simulated annealing is used for the first time to solve reconfiguration power loss reduction problem in **[6, 7]**. It is presented as a non-differentiable multiple objective function combinatorial optimization problem with constraints.

However, the switch reconfiguration algorithms reported in the literature do not treat capacitors and capacitor algorithms do not treat switch reconfiguration. In this paper, we present a single comprehensive algorithm for distribution system switch reconfiguration and capacitor control. Necessity to consider both capacitor switching and switch reconfiguration in order to achieve optimal loss minimization is presented in**[8]**. It was concluded that joint reconfiguration and capacitor control achieves acceptable voltages without the need to activate the regulators.

In **[9, 10]** the objective of the analyses is to outline and validate a methodology for the optimization of MV distribution networks operation, so that variable loads are fed under minimum energy losses. Loss minimization is achieved by the installation of shunt capacitors and reconfiguration of the network. It is noticable that for the tested network 11,36% loss reduction is achieved by the network reconfiguration and 18,6% by the capacitor installation.

Authors in **[11]** present three heuristic methods for radial distribution networks reconfiguration and capacitor control. A simulated annealing algorithm, a genetic algorithm and a tabu search algorithm with some adaptations have been applied and compared. Test results demonstrate that the tabu search algorithm type outperforms the other heuristics.

As a cornerstone of this paper, the article of Nahman and Perić **[12]** is used. The connectivity check criterion (presented in section 2) that was refined. The efficient power flow algorithm applied here is in MATPOWER environment **[13]**. Fundamentals for simulated annealing algorithm programming are borrowed from Masters work **[14]**.

## NETWORK CONNECTIVITY CHECK

Power network is connected if there is a path between any pair of its nodes. This means that all load nodes are connected to the source node and can be supplied from that node. Network connectivity can be easily checked by means of matrix $(NC)$ defined as **[15]**:

$$(NC) = (B)exp(n-1), \qquad (2.1)$$

where $n$ is the number of network nodes and $(B)$ is $n\,x\,n$ system connectivity matrix with elements $B\,(i,j)$ equal to 1 if there is a line between nodes $i$ and $j$, and 0 otherwise. When $i = j$ in accordance with convention **[15]** $B\,(i,j)$ equals 1. Network is connected if all $(NC)$ matrix elements equal 1 **[15]**. Arithmetic operations in (2.1) are Boolean, which means:

$0 + 0 = 0;$

$0 + 1 = 1 + 1 = 1;$

$0 * 0 = 0;$

$1 * 1 = 1$ and

$1 * 0 = 0.$

One of the applications of matrix $B$ is to check if the distribution system is connected.

Distribution system topology can be presented by graph with $m$ branches and $n$ nodes (buses) **[16]**. It can be stated that distribution network topology is radial if it satisfies the following two conditions **[16]**:

- Configuration must have $n-1$ branches;
- Configuration must be connected.

## Precise Matpower Efficient Power Flow ('case33bw')

Many problems related to the distribution system real application as optimization, capacitor placement, voltage regulation, planning, restauration, state estimation, and so on, seek precise efficient power flow algorithm for network voltage (branch current) and loss calculation.

Widely adopted is the forward/backward sweep method where cumbersome input data feeding for level drawn network is exploited. The biggest drawback of these procedures is that data input must be generated and fed all the time, for each new configuration, which makes them practically useless for dynamic problems such as network reconfiguration and expansion planning.

The MATPOWER algorithm **[13]** applied in this paper is novel and classical. The default solver is based on a standard Newton's method using a polar form and a full Jacobian updated at each iteration. No renumeration of nodes is necessary. The analyzed network can be radial or weakly meshed.

Applied algorithm represents powerful weapon of every distribution engineer when solving dynamic distribution network problems such as their reconfiguration or planning.

## The Block Diagram Reconfiguration and Capacitor Switching Simultaneously (Figure 1)

The following data are in the output file of the developed MATLAB programme.

Ploss - the active power loss of the current configuration.

E- price for the last generated configuration by simulated annealing ($).

EOLD - price for the last accepted configuration by simulated annealing ($).

EOLDD - price that is minimal during the whole procedure of performing simulated annealing (greedy search of all generated configurations) in $.

Niz - vector denoting open branches for the last generated configuration.

Niz OLD- vector denoting open branches for the last accepted configuration.

Niz OLDD- vector denoting open branches linked with EOLDD price.

QBK- vector denoting installed capacitors for the last generated configuration.

QBKOLD- vector denoting installed capacitors for the last accepted configuration.

QBKOLDD- vector denoting installed capacitors linked with EOLDD price.

IMIN - number of generated minimal configurations (by monitoring greedy search) in descending order.

## Numerical Results

The tested system is hypothetical 12.66 kV system **[3]** (given in Figure 2) comprising of 32 branches and 5 tie switches forming 5 different loops when closed. System data are given in Tables 1, 2 and 3. The total active and reactive load of tested network amount to 3715 kW and 2300 kVar respectively. Total system active power loss is 202.675 kW (precise power loss **[13]**) which is 5.5 % of total active power demand. The network is not well compensated. Its input cosφ is 0.8493 (< 0.85). The capacitor price step up function is given in Table 4. Let maximum tolerances of node voltages be ±10 % (of 12.66 kV).

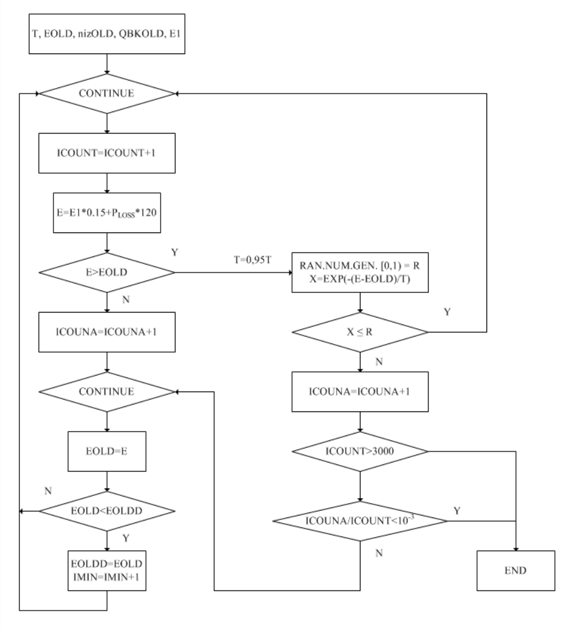


**Figure1.** *The Block Diagram*

The lowest voltage of the initial configuration is 0.9131 p.u. (nominal load level) so the node voltages are not critical. It is also supposed that each branch can be opened or closed by means of sectionalizing switch and that capacitor banks in 300 kVar step can be installed in any node but the slack one.

Target optimum, global optimum is known for example network and reconfiguration alone (Figure 2). With added capacitors it is also the cheapest configuration. Cosφ is an input power factor of calculated networks (obtained solutions).

In Tables 1, 2 and 3 shaded figure in | V | p.u. column denotes the lowest node voltage.

In Tables 1, 2 and 3 shaded figures in the branch Ploss column denote losses of branches greater than in initial configuration.

Zeros in A column denote open branches.

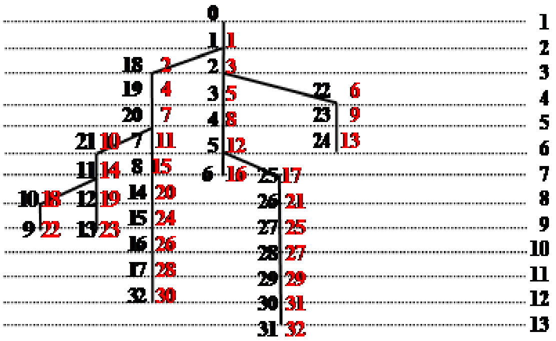

**Figure2.** *The cheapest configuration*

*8 node (0,3 Mvar), 24 node (0,3 Mvar) and 29 node (0,9 Mvar)*

## Discussion and Conclusions

The worst lowest voltage of all three algorithms is 0.956 p.u. (reconfiguration and capacitor switching simultaneously) which is better than the previous value 0.9131 p.u. of initial configuration. Significantly, the combined switch reconfiguration and capacitor control allows tight control of node voltages even without activating voltage regulators. Reducing the bandwidth of delivered voltages can be used to improve the efficiency of motors and other voltage sensitive devices. Lowering losses and reducing voltage bandwidths will become more attractive as distribution systems are loaded closer to their ultimate limits.

It can be noted that the minimum loss configuration is the reconfiguration and then capacitor switching configuration for which losses amount to 93.887 kW (reduction 53,65% of the initial configuration losses, for the other two configurations reduction is also very close to 50%). It is also the cheapest configuration (12511 $). This conclusion does not comply with computational results **[1, 2]** which show that by taking into account the feeder reconfiguration and capacitor settings simultaneously, one can minimize losses more efficiently than by considering them separately. As suboptimum is reached by the authors for simultaneous algorithm, it cannot be stated for sure which algorithm is the best.

The most economic configuration (when nominal load level is considered) in the presented research is the reconfiguration and then capacitor switching configuration 12511 $, saving 11801 $, 48.5 % (Figure 2). All savings related to the cost of initial, “bare” configuration.

It can be observed that the fastest is the simultaneous algorithm (1 h 20 min) because of the input parameters which are not rigorous.

**Table1.** *Input data and results (Ploss=97,9408 kW) for configuration 7, 36, 37, 11 and 34 branches open (zeros in A column) node 12 (0,6 Mvar), node 23 (0,3 Mvar) and node 29 (0,9 Mvar) Reconfiguration and capacitor switching simultaneously. 13193$, cosφ=0,9890*

| branch | R (Ω) | X (Ω) | Pload (kW) | Qload (kVar) | \| V \| p.u. | Ibranch modul (A) | branch Ploss (MW) | branch Qloss (Mvar) |
|---|---|---|---|---|---|---|---|---|
| 0-1 | 0.0922 | 0.0470 | 100.00 | 60.00 | 0.998 | | 0.009 | 0.00 |
| 1-2 | 0.4930 | 0.2511 | 90.00 | 40.00 | 0.989 | | 0.019 | 0.01 |
| 2-3 | 0.3660 | 0.1864 | 120.00 | 80.00 | 0.986 | | 0.005 | 0.00 |
| 3-4 | 0.3811 | 0.1941 | 60.00 | 30.00 | 0.982 | | 0.004 | 0.00 |
| 4-5 | 0.8190 | 0.7070 | 60.00 | 20.00 | 0.975 | | 0.008 | 0.01 |
| 5-6 | 0.1872 | 0.6188 | 200.00 | 100.00 | 0.975 | | 0.000 | 0.00 |
| 6-7 | 0.7114 | 0.2351 | 200.00 | 100.00 | 0.976 | 0 | - | - |
| 7-8 | 1.0300 | 0.7400 | 60.00 | 20.00 | 0.975 | | 0.000 | 0.00 |
| 8-9 | 1.0440 | 0.7400 | 60.00 | 20.00 | 0.974 | | 0.000 | 0.00 |
| 9-10 | 0.1966 | 0.0650 | 45.00 | 30.00 | 0.974 | | 0.000 | 0.00 |
| 10-11 | 0.3744 | 0.1238 | 60.00 | 35.00 | 0.980 | 0 | - | - |
| 11-12 | 1.4680 | 1.1550 | 60.00 | -565.00 | 0.979 | | 0.003 | 0.00 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 12-13 | 0.5416 | 0.7129 | 120.00 | 80.00 | 0.977 | | 0.001 | 0.00 |
| 13-14 | 0.5910 | 0.5260 | 60.00 | 10.00 | 0.975 | | 0.000 | 0.00 |
| 14-15 | 0.7463 | 0.5450 | 60.00 | 20.00 | 0.974 | | 0.000 | 0.00 |
| 15-16 | 1.2890 | 1.7210 | 60.00 | 20.00 | 0.972 | | 0.000 | 0.00 |
| 16-17 | 0.7320 | 0.5740 | 90.00 | 40.00 | 0.972 | | 0.000 | 0.00 |
| | | | | | | | | |
| 1-18 | 0.1640 | 0.1565 | 90.00 | 40.00 | 0.996 | | 0.002 | 0.00 |
| 18-19 | 1.5042 | 1.3554 | 90.00 | 40.00 | 0.986 | | 0.013 | 0.01 |
| 19-20 | 0.4095 | 0.4784 | 90.00 | 40.00 | 0.983 | | 0.003 | 0.00 |
| 20-21 | 0.7089 | 0.9373 | 90.00 | 40.00 | 0.982 | | 0.002 | 0.00 |
| | | | | | | | | |
| 2-22 | 0.4512 | 0.3083 | 90.00 | 50.00 | 0.986 | | 0.003 | 0.00 |
| 22-23 | 0.8980 | 0.7091 | 420.00 | -100.00 | 0.981 | | 0.004 | 0.00 |
| 23-24 | 0.8960 | 0.7011 | 420.00 | 200.00 | 0.978 | | 0.001 | 0.00 |
| | | | | | | | | |
| 5-25 | 0.2030 | 0.1034 | 60.00 | 25.00 | 0.974 | | 0.001 | 0.00 |
| 25-26 | 0.2842 | 0.1447 | 60.00 | 25.00 | 0.972 | | 0.001 | 0.00 |
| 26-27 | 1.0590 | 0.9337 | 60.00 | 20.00 | 0.967 | | 0.005 | 0.00 |
| 27-28 | 0.8042 | 0.7006 | 120.00 | 70.00 | 0.963 | | 0.003 | 0.00 |
| 28-29 | 0.5075 | 0.2585 | 200.00 | -300.00 | 0.961 | | 0.001 | 0.00 |
| 29-30 | 0.9744 | 0.9630 | 150.00 | 70.00 | 0.957 | | 0.001 | 0.00 |
| 30-31 | 0.3105 | 0.3619 | 210.00 | 100.00 | 0.956 | | 0.000 | 0.00 |
| 31-32 | 0.3410 | 0.5302 | 60.00 | 40.00 | 0.956 | | 0.000 | 0.00 |
| | | | | | | | | |
| 7-20, 33 | 2.000 | 2.000 | | | | | 0.002 | 0.002 |
| 8-14, 34 | 2.000 | 2.000 | | | | 0 | - | - |
| 11-21, 35 | 2.000 | 2.000 | | | | | 0.005 | 0.005 |
| 17-32, 36 | 0.500 | 0.500 | | | | 0 | - | - |
| 24-28, 37 | 0.500 | 0.500 | | | | 0 | - | - |

**Table2.** *Input data and results (Ploss=93,8 kW) for configuration 7, 9, 32, 37 and 14 branches open (zeros in A column) 8 node (0,3 Mvar), 24 node (0,3 Mvar) and 29 node (0,9 Mvar)Reconfiguration and then capacitor switching.12511$, cosφ=0,9749*

| branch | R (Ω) | X (Ω) | Pload (kW) | Qload (kVar) | \| V \| p.u. | Ibranch modul (A) | branch Ploss (MW) | branch Qloss (Mvar) |
|---|---|---|---|---|---|---|---|---|
| 0-1 | 0.0922 | 0.0470 | 100.00 | 60.00 | 0.998 | | 0.009 | 0.00 |
| 1-2 | 0.4930 | 0.2511 | 90.00 | 40.00 | 0.990 | | 0.018 | 0.01 |
| 2-3 | 0.3660 | 0.1864 | 120.00 | 80.00 | 0.986 | | 0.004 | 0.00 |
| 3-4 | 0.3811 | 0.1941 | 60.00 | 30.00 | 0.983 | | 0.004 | 0.00 |
| 4-5 | 0.8190 | 0.7070 | 60.00 | 20.00 | 0.976 | | 0.007 | 0.01 |
| 5-6 | 0.1872 | 0.6188 | 200.00 | 100.00 | 0.976 | | 0.000 | 0.00 |
| 6-7 | 0.7114 | 0.2351 | 200.00 | 100.00 | 0.971 | 0 | - | - |
| 7-8 | 1.0300 | 0.7400 | 60.00 | -280.00 | 0.969 | | 0.001 | 0.00 |
| 8-9 | 1.0440 | 0.7400 | 60.00 | 20.00 | 0.967 | 0 | - | - |
| 9-10 | 0.1966 | 0.0650 | 45.00 | 30.00 | 0.967 | | 0.000 | 0.00 |
| 10-11 | 0.3744 | 0.1238 | 60.00 | 35.00 | 0.968 | | 0.000 | 0.00 |
| 11-12 | 1.4680 | 1.1550 | 60.00 | 35.00 | 0.965 | | 0.000 | 0.00 |
| 12-13 | 0.5416 | 0.7129 | 120.00 | 80.00 | 0.964 | | 0.000 | 0.00 |
| 13-14 | 0.5910 | 0.5260 | 60.00 | 10.00 | 0.963 | 0 | - | - |
| 14-15 | 0.7463 | 0.5450 | 60.00 | 20.00 | 0.961 | | 0.000 | 0.00 |
| 15-16 | 1.2890 | 1.7210 | 60.00 | 20.00 | 0.958 | | 0.000 | 0.00 |
| 16-17 | 0.7320 | 0.5740 | 90.00 | 40.00 | 0.957 | | 0.000 | 0.00 |
| | | | | | | | | |
| 1-18 | 0.1640 | 0.1565 | 90.00 | 40.00 | 0.996 | | 0.002 | 0.00 |
| 18-19 | 1.5042 | 1.3554 | 90.00 | 40.00 | 0.982 | | 0.015 | 0.01 |
| 19-20 | 0.4095 | 0.4784 | 90.00 | 40.00 | 0.978 | | 0.004 | 0.00 |
| 20-21 | 0.7089 | 0.9373 | 90.00 | 40.00 | 0.975 | | 0.001 | 0.00 |
| | | | | | | | | |
| 2-22 | 0.4512 | 0.3083 | 90.00 | 50.00 | 0.987 | | 0.003 | 0.00 |
| 22-23 | 0.8980 | 0.7091 | 420.00 | 200.00 | 0.981 | | 0.004 | 0.00 |
| 23-24 | 0.8960 | 0.7011 | 420.00 | -100.00 | 0.979 | | 0.001 | 0.00 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 5-25 | 0.2030 | 0.1034 | 60.00 | 25.00 | 0.975 | | 0.001 | 0.00 |
| 25-26 | 0.2842 | 0.1447 | 60.00 | 25.00 | 0.974 | | 0.001 | 0.00 |
| 26-27 | 1.0590 | 0.9337 | 60.00 | 20.00 | 0.969 | | 0.004 | 0.00 |
| 27-28 | 0.8042 | 0.7006 | 120.00 | 70.00 | 0.966 | | 0.003 | 0.00 |
| 28-29 | 0.5075 | 0.2585 | 200.00 | -300.00 | 0.964 | | 0.001 | 0.00 |
| 29-30 | 0.9744 | 0.9630 | 150.00 | 70.00 | 0.961 | | 0.001 | 0.00 |
| 30-31 | 0.3105 | 0.3619 | 210.00 | 100.00 | 0.960 | | 0.000 | 0.00 |
| 31-32 | 0.3410 | 0.5302 | 60.00 | 40.00 | 0.957 | 0 | - | - |
| 7-20, 33 | 2.000 | 2.000 | | | | | 0.005 | 0.005 |
| 8-14, 34 | 2.000 | 2.000 | | | | | 0.002 | 0.002 |
| 11-21, 35 | 2.000 | 2.000 | | | | | 0.002 | 0.002 |
| 17-32, 36 | 0.500 | 0.500 | | | | | 0.00 | 0.00 |
| 24-28, 37 | 0.500 | 0.500 | | | | 0 | - | - |

**Table3.** *Input data and results (Ploss=95,123 kW) for configuration 36, 14, 7, 28 and 9 branches open (zeros in A) node 6 (0,3 Mvar), node 13 (0,3 Mvar), node 24 (0,3 Mvar) and node 29 (0,9 Mvar)Capacitor switching and then reconfiguration.12945$, cosφ=0,9890*

| branch | R (Ω) | X (Ω) | Pload (kW) | Qload (kVar) | \| V \| p.u. | Ibranch Modul (A) | Branch Ploss (MW) | branch Qloss (Mvar) |
|---|---|---|---|---|---|---|---|---|
| 0-1 | 0.0922 | 0.0470 | 100.00 | 60.00 | 0.998 | | 0.009 | 0.00 |
| 1-2 | 0.4930 | 0.2511 | 90.00 | 40.00 | 0.990 | | 0.019 | 0.01 |
| 2-3 | 0.3660 | 0.1864 | 120.00 | 80.00 | 0.988 | | 0.001 | 0.00 |
| 3-4 | 0.3811 | 0.1941 | 60.00 | 30.00 | 0.987 | | 0.001 | 0.00 |
| 4-5 | 0.8190 | 0.7070 | 60.00 | 20.00 | 0.985 | | 0.001 | 0.00 |
| 5-6 | 0.1872 | 0.6188 | 200.00 | -200.00 | 0.986 | | 0.000 | 0.00 |
| 6-7 | 0.7114 | 0.2351 | 200.00 | 100.00 | 0.970 | 0 | - | - |
| 7-8 | 1.0300 | 0.7400 | 60.00 | 20.00 | 0.967 | | 0.001 | 0.00 |
| 8-9 | 1.0440 | 0.7400 | 60.00 | 20.00 | 0.974 | 0 | - | - |
| 9-10 | 0.1966 | 0.0650 | 45.00 | 30.00 | 0.974 | | 0.000 | 0.00 |
| 10-11 | 0.3744 | 0.1238 | 60.00 | 35.00 | 0.975 | | 0.000 | 0.00 |
| 11-12 | 1.4680 | 1.1550 | 60.00 | 35.00 | 0.974 | | 0.001 | 0.00 |
| 12-13 | 0.5416 | 0.7129 | 120.00 | -220.00 | 0.975 | | 0.000 | 0.00 |
| 13-14 | 0.5910 | 0.5260 | 60.00 | 10.00 | 0.962 | 0 | - | - |
| 14-15 | 0.7463 | 0.5450 | 60.00 | 20.00 | 0.961 | | 0.000 | 0.00 |
| 15-16 | 1.2890 | 1.7210 | 60.00 | 20.00 | 0.959 | | 0.000 | 0.00 |
| 16-17 | 0.7320 | 0.5740 | 90.00 | 40.00 | 0.959 | | 0.000 | 0.00 |
| 1-18 | 0.1640 | 0.1565 | 90.00 | 40.00 | 0.996 | | 0.002 | 0.00 |
| 18-19 | 1.5042 | 1.3554 | 90.00 | 40.00 | 0.983 | | 0.014 | 0.01 |
| 19-20 | 0.4095 | 0.4784 | 90.00 | 40.00 | 0.979 | | 0.003 | 0.00 |
| 20-21 | 0.7089 | 0.9373 | 90.00 | 40.00 | 0.978 | | 0.001 | 0.00 |
| 2-22 | 0.4512 | 0.3083 | 90.00 | 50.00 | 0.985 | | 0.008 | 0.01 |
| 22-23 | 0.8980 | 0.7091 | 420.00 | 200.00 | 0.975 | | 0.015 | 0.01 |
| 23-24 | 0.8960 | 0.7011 | 420.00 | -100.00 | 0.969 | | 0.008 | 0.01 |
| 5-25 | 0.2030 | 0.1034 | 60.00 | 25.00 | 0.985 | | 0.000 | 0.00 |
| 25-26 | 0.2842 | 0.1447 | 60.00 | 25.00 | 0.985 | | 0.000 | 0.00 |
| 26-27 | 1.0590 | 0.9337 | 60.00 | 20.00 | 0.984 | | 0.000 | 0.00 |
| 27-28 | 0.8042 | 0.7006 | 120.00 | 70.00 | 0.966 | 0 | - | - |
| 28-29 | 0.5075 | 0.2585 | 200.00 | -300.00 | 0.965 | | 0.001 | 0.00 |
| 29-30 | 0.9744 | 0.9630 | 150.00 | 70.00 | 0.961 | | 0.001 | 0.00 |
| 30-31 | 0.3105 | 0.3619 | 210.00 | 100.00 | 0.960 | | 0.000 | 0.00 |
| 31-32 | 0.3410 | 0.5302 | 60.00 | 40.00 | 0.959 | | 0.000 | 0.00 |
| 7-20, 33 | 2.000 | 2.000 | | | | | 0.004 | 0.004 |
| 8-14, 34 | 2.000 | 2.000 | | | | | 0.001 | 0.001 |
| 11-21, 35 | 2.000 | 2.000 | | | | | 0.002 | 0.002 |
| 17-32, 36 | 0.500 | 0.500 | | | | 0 | - | - |
| 24-28, 37 | 0.500 | 0.500 | | | | | 0.002 | 0.002 |

**Table4.** *Capacitor price step up function*

| **Capacitor rating** | **> 0, ≤ 300 kVar** | **> 300, ≤ 600 kVar** | **> 600, ≤ 900 kVar** | **> 900, ≤ 1200 kVar** | **> 1200 kVar** |
|---|---|---|---|---|---|
| price | 1900 $ | 3200 $ | 4500 $ | 5400 $ | 6000 $ |
| Maintenance and installation cost is included in fixed part of the price. | | | | | |

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