Josip PAVLEKA[1], Srete NIKOLOVSKI [2], Marinko STOJKOV[3]

Josip Pavleka, HEP - Distribution System Operator Ltd., Zagreb, Croatia (1),
Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, Croatia (2),
Mechanical Engineering Faculty in Slavonski Brod, Croatia (3)

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Finding Optimal Location of FACTS device for dynamic Reactive Power compensation using Genetic Algorithm and Particle Swarm Optimisation (PSO)

***Abstract**. This paper presents advantage of using a FACTS device for dynamic Reactive Power compensation. Simulation model was built in MATLAB Simulink software to prove mathematical constraints. Determination of the most favourable location and size of the compensation devices from the aspect of losses, power quality, costs are calculated as a fitness function developed by genetic algorithm. Optimisation was done by Particle swarm optimization (PSO). Finally, cut convergence time and significant potential of usage such type of PSO optimisation method for determination of future investments are shown. This algorithm is tested to determine optimal location of FACTS device in railway application, instead of the methods and algorithms in transmission or distribution power system used until now.*

Streszczenie.** W artykule zaprezentowano korzyści ze stosowanie FACTS do dynamicznej kompensacji mocy biernej. Symulacje miały na celu określenie najlepszego położenia i roz,miaru urządzeń kompensujących z punktu widzenia jakości energii i kosztów. Zastosowano algorytm genetyczny PSO do optymalizacji i analizy przyszłych inwestycji.* ***Optymalna lokalizacja FACTS do dynamicznej kompensacji mocy biernej z wykorzystaniem algorytmu genetycznego

Keywords: FACTS, Reactive Power Compensation, Genetic Algorithm, Particle Swarm Optimisation, Determination of Optimal Location
Słowa kluczowe: FACTS, kompensacja mocy biernej, algorytm genetyczny, optymalna lokalizacja

Introduction

Reactive power is of great importance for the operation of the AC power system. A power system consists of different elements. Some of them can be modelled as the electricity containers, such as coils and capacities. Since the AC circuits imply continually electric current and voltage changes, these containers constantly store and release energy. During a specific time period, the total energy consumption of these components equals zero. The energy flowing between the elements for energy storage does not perform useful (active) work, but that reactive energy is inevitably a part of total energy, together with the useful (active) energy, which feeds the load. However, the flow of this energy is required in order to retain the required change of the magnetic and electrical fields of these energy containers. The energy flowing as the reaction to the activity of these elements is called reactive power. Despite the fact that the energy does not perform any useful work, it is still important for maintaining the stability of the system operation. Maintaining a balance between consumption and generation of reactive power has been the subject of numerous scientific papers since the commencement of commercial use of EPS.

Simulation of the operation of the non-linear load with the active power filter in the programme package MATLAB simulink

The programme package MATLAB Simulink simulates the operation of the non-linear load to the purpose of the analysis of the impact of the dynamic reactive power regulation by application of the active power filter. The model was created in line with the theory of the momentary power values. Fig. 1 shows the simulation model of the reactive power dynamic compensation of the non-linear load in the
MATLAB Simulink. The power supply source is shown through the three phase source of the sinusoidal voltage, with effective value of the interphase voltage of 400 V. The phase windings are star-coupled, while the neutral point is directly connected to the earth potential (zero potential), frequency 50 Hz, where initial phase shift of phase L1 is zero degrees, and phase-to-phase shift is 120º (symmetrical system). The simulation model also includes the block which models the impendence of the phase conductors to the Point of Common Coupling (PCC), which in fact represents a common point of the load connection to the low-voltage three-phase source. At the exit of this block it is possible to obtain the phase voltages and currents of the power supply source (voltage source), marked on Fig. below as Uc and Ic. The subsystems of the non-linear load and the active power filter ("Shunt APF") are also tied to the PCC. At the exit of the non-linear load subsystem there is a block, marked as Iload, whose role is to send the measured values of the phase load currents to the relevant block in the developed scheme of the subsystem represented by the non-linear load.

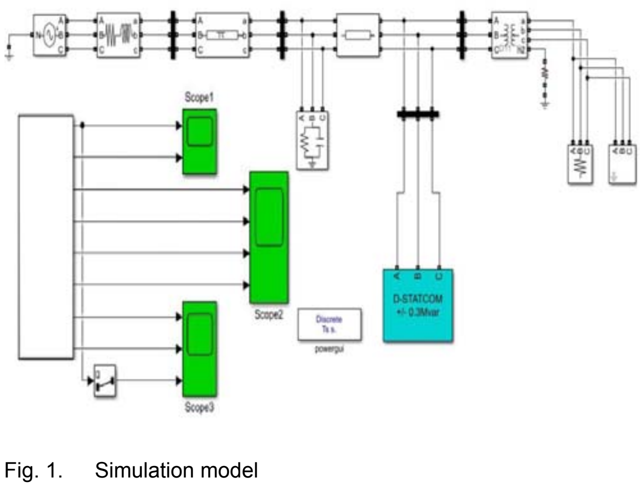


Fig. 1. Simulation model

Fig. 2. shows the subsystem, which represents the active power filter (Shunt APF). The basic role of the active power filter is to form at its exit a set of the three phase compensation currents, which are realised through an inverter bridge by application of the IGBT transistors and diodes as the switch elements. The DC voltage of the invertor bridge is obtained by application of the two

capacities sections, each of 400 μF, which represent the energy source for the formation of the compensation phase currents, at the exit from the invertor. These currents are injected in the PCC.

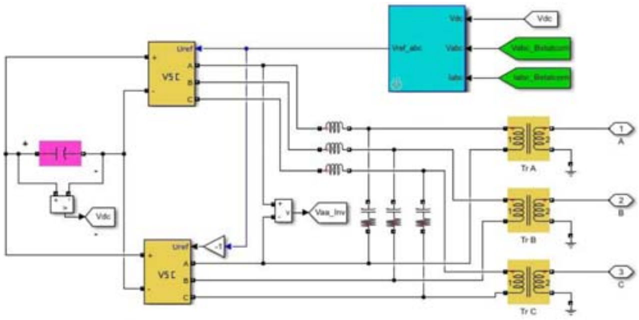
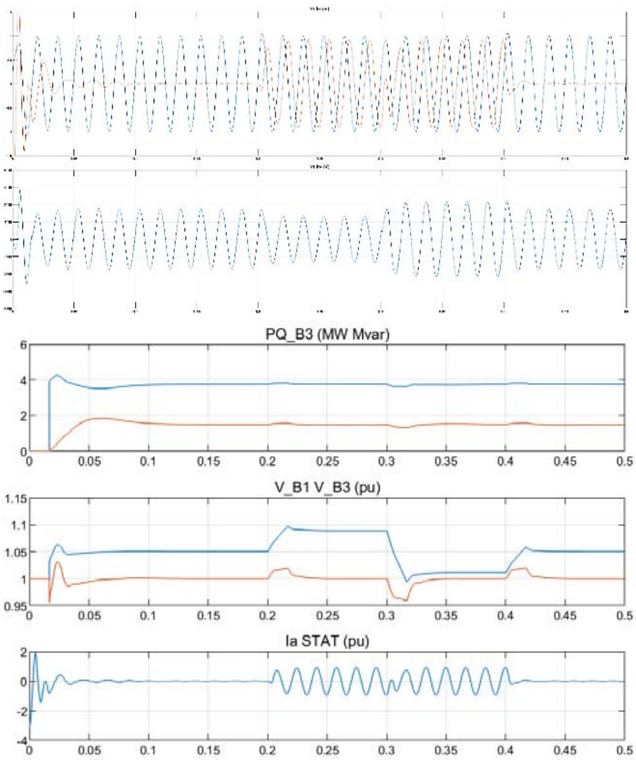


Fig. 2. Simulation sub-model

The role of the PI controller is to reduce the active power losses caused by the oscillations of the active DC voltage. The figure. also shows the block for calculation of the necessary active and reactive power, according to the theory of the momentary power values, which should be compensated. Based on these two power values (active and reactive) the previously mentioned block calculates the relevant compensation currents. These currents are used as referential currents, which are compared with the measured values of phase currents of the load. Using the hysteresis controller these two currents are compared, and based on this comparison the controlling currents of the controller electrodes (Gate) of the IGBT transistor are generated. Controlling currents regulate the periods of switching-on and off of the particular switching elements, with aim to generate and inject the compensation phase currents in the PCC in the real time.

Analysis of the results of simulation of the reactive power dynamic compensation

Fig. 3. shows the temporal changes of the phase voltages of the power supply sources:



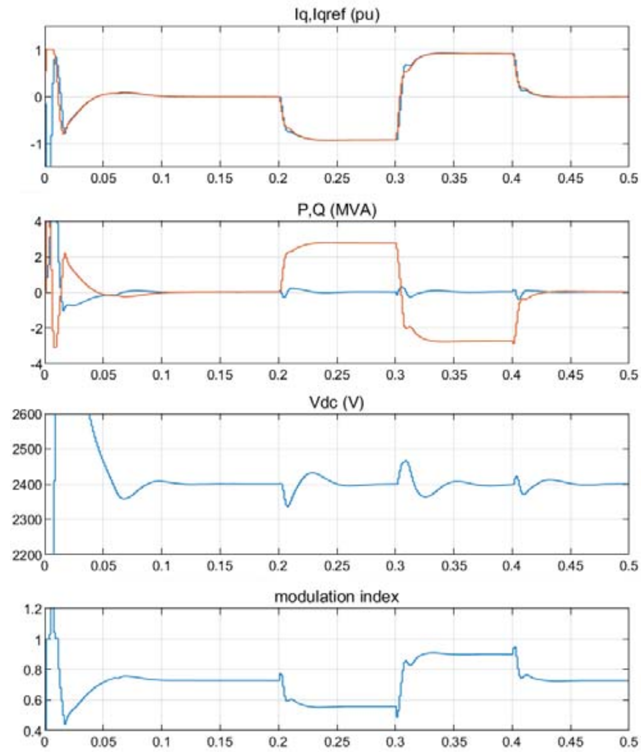


Fig. 3. Output curves as results from simulation

Determination of the compensation power

For the analysis of the electricity consumption data, the archive-measured data for the electricity taken from the HOPS transmission network are used.

The figure below shows the trends of the active and reactive power consumption (inductive component) and the power factors for Electric Traction Station (ETS) in period from 1987, when the plant was built and put into operation, until 2014.

It is easy to see from the Figure that the taken active and reactive power in ETS in the last five-six years is decreasing and that the power factor is around 0,8.

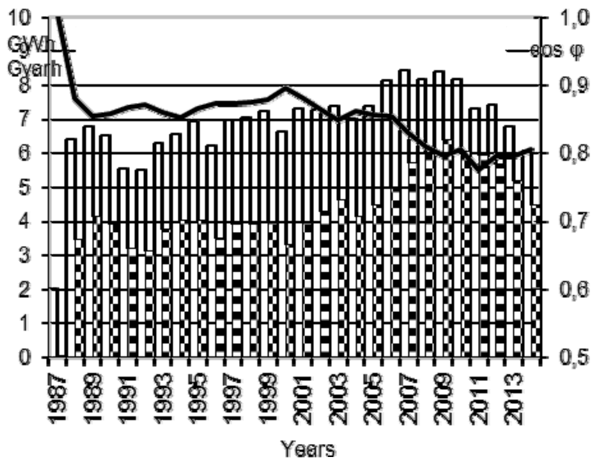


Fig. 4. Energy consumed in ETS from 1987 to 2014

In order to be able to estimate the consumption for the following years, at first the consumption trends in the past years have to be analysed.

Table 1 shows the trends of the taken active and reactive power and power factors for ETS from 2009 to 2014.

Table 1. Energy consumption growth

Indicator / yr.	2009	201.	2011	2012	2013	2014
Active energy, MWh	8.398,2	8.182,0	7.322,2	7.435,2	6.814,5	6.082,9
Active power - growth, %		-2,57	-10,51	1,54	-8,35	-10,74
Reactive energy, MVArh	6.400,7	6.032,8	5.951,8	5.669,7	5.167,7	4.470,4
Reactive power - growth, %		-5,75	-1,34	-4,74	-8,85	- 13,49
Power factor	0,7953	0,8049	0,7760	0,7952	0,7698	0,8058

From the data given in Table 1 it is evident that estimation of the consumption growth for the following years, based on the consumption from the previous years, is impossible. Considering that there aren't any relevant official data for the consumption forecast, estimated growth is assumed as 1,5 %, in relation to the consumption in 2014 as reference.

Mathematical model

Determination of the most favourable location and size of the compensation devices from the aspect of decreasing the active power losses:

The first task in determining the target function is to decrease the active power losses:

$$(1) \qquad \min f_1 = P_{loss} \sum_{i=1}^{m} R_l I_l^2$$

$$= \left[\sum_{i=1}^{n} \sum_{i=1, i\neq j}^{n} V_i^2 + V_j^2 - 2V_i V_j \cos\Theta_i - \Theta_j \right] Y_{ii} \cos\Theta_{ij}$$

where m is the number of outlets, n is the number of the bus bars, R is resistance per outlet, I_i the current of the outlet I, V_i is the value and the θ_i is angle of the voltage on the bus bar i, Y_{ii} is the value and θ_{ij} is the angle of the outlet admittance.

- Minimum voltage deviation:

The FACTS devices connected in an adequate place may have a leading role in improvement of the voltage profile and voltage distortions reduction in the power system.

So, the second target is to reduce the variation of the bus bar voltage. This target function may be expressed also as:

$$(2) \qquad \min f_2 = \sum_{i=1}^{n} \left| V_{iref} - V_i \right|$$

where V_i stands for the value of the voltage on the bus bar and, V_{iref} is the rated bus bar voltage i.

The equations specified below describe active and reactive power:

$$(3) \qquad P_{Gi} - P_{Di} = V_i \sum_{j=1}^{n} V_j (G_{ij} \cos\Theta_{ij} + B_{ij} \sin\Theta_{ij})$$

$$(4) \qquad Q_{Gi} - Q_{Di} = V_i \sum_{j=1}^{n} V_j (G_{ij} \sin\Theta_{ij} + B_{ij} \cos\Theta_{ij})$$

The problem of determination of the optimal locations and rated power of the STATCOM is required to be resolved for the different target functions, and also the minimization of THD_V has to be taken into consideration.

- Minimization of THD_{Vi}:

$$(4) \qquad \min f_3 = \sum_{i=1}^{n} \max(THD_{Vi}),$$

where THD_{Vi} is the total harmonic voltage distortion in the node i, and n is the last node in the grid. The following expression is applied:

- Target function of STATCOM:

$$(5) \qquad P_{D-STATCOM} = \frac{V_k V_{D-STATCOM}}{V_{k,D-STATCOM}} \sin(\delta_k - \delta_{D-STATCOM})$$

$$(6) \qquad Q_{D-STATCOM} = \frac{V_k \{ V_{D-STATCOM} \cos(\delta_k - \delta_{D-STATCOM}) - V_k \}}{V_{k,D-STATCOM}}$$

- Cost function of the power facility build-up:

$$(7) \qquad \min f_4 = C_{stat} = \frac{\sum_{i=1}^{k} \left(\alpha S_{stat-i}^2 - \beta S_{stat-i} + C_{0-i} \right)}{Cost_{max}}$$

where the C_{stat}, C_0, and S_{stat} are total costs, fixed costs of installation and costs emerged due to use of D-STATCOM, and α and β are fixed coefficients with defined values 0,0002478 and 0,2261, [Cai, 2004].

Total cost saving from DSTATCOM is the difference between the costs of the total energy losses before construction of the facility, and the costs of the total energy losses after facility construction.

- Target function OptiLOK (optimal place of installation):

In determination of the target function, and of the optimal location for installation, it is required to find the minimum of the target function, so it follows:

min f(x), or, expanded:

$$(7) \qquad \min f(x) = w_1 f_1 + w_2 f_2 + w_3 f_3 + \lambda_v \sum_{i \in M} \begin{bmatrix} \max(V_i - V_{i-max}, 0) \\ + \max(V_{i-min} - V_i, 0) \end{bmatrix} + \lambda_{APC} \sum_{i \in P} \begin{bmatrix} \max(s_{stat} - s_{stat-max}, 0) \\ + \max(s_{stat-min} - S_{APC}, 0) \end{bmatrix}$$

w_1, w_2 and w_3 are here the weighting coefficients, where the following condition is valid: w_1+w_2+w_3=1.

Optimisation algorithm

The genetic algorithm (GA) is a robust and adaptive method founded on the evolution and genetics principles [8]. GA belongs to the group of the population-iterative methods, and is successfully used for problem-solving of numerical optimisation. The basic building element of GA is a chromosome. The quality of each chromosome is quantified over time in the node and at the h^{-th} harmonic.

$(\underline{V}(h))^{(k-1)}$ - the complex node voltage i from the preceding iteration at the h^{-th} harmonic.

The search process in GA begins with a randomly picked set of solutions, that is, a number of chromosomes, mostly encoded as the binary string (data series) of definite length. Each string represents a possible solution to the problem, and each information (gene) in the string represents a state variable in this problem. Since these are the parts of the string, they can be called substrings. Specific string structure is characteristic for the problem of the optimal locations and defining of rated power of capacity banks (CB). In this case the substring includes the information of the location and rated power of the CB. The number of the substrings and the string length depends on the number of the variables which are optimised, i.e. on the number of CB (N_C) for which the optimal locations and rated power have to be determined. In each generation, the value of the fitness function, which is related to the value of the target function in the problem of optimisation, which is being resolved, each chromosome in the population is being evaluated. In this paper, the evaluation of the fitness function value is calculated by the algorithm. Depending on the obtained fitness function value, different operators are applied to the chromosomes, to the purpose of the favouring of the chromosomes which are closest to the problem solution. The basic operators, which perform operations on the genes to the purpose of replacement of their place within the chromosome itself, are selection, crossing and mutation. Generally, one generation can be split into two phases [14]. Early in the process there is a single initial population. Selection makes possible the elimination of bad chromosomes (solutions) and survival of the better-quality chromosomes, thus creating an inter-population (parents' pairs). In fact, the selection is the process in which particular genes are transferred io the next generation. After selection, in the second phase, the crossing and mutation operators are applied. Crossing is a process in which by way of exchange of the parents' genes, two new individuals (children), are created. After crossing, the mutation is also performed, in order to change the characteristics of the newly created individuals by the random change of the genes. In this way it is accomplished that the individuals become increasingly better from one generation to the other, which means that the values of the variable states approximate to the optimal values.

GA process is stopped when the maximum number of generations is created, or when the satisfactory fitness level for the population is reached. The GA performances to a large extent depend on the correct setting of the control parameters. Unfortunately there is no universal rule for this setting, but it is performed based on experience, that is on the trial-and-error basis.

A Particle Swarm Optimisation (PSO)

It represents the new evolutionary computer-based technology first introduced by Kennedy and Eberhart [15]. The development of their idea was based on the simulation of the animal social behaviour, such as the flock of birds, school of fish or groups of people who pursue a common goal in their life. PSO was initialized by generating the random solution population, called a "swarm". Each individual is called a particle and represents a candidate solution to the problem. The position of each particle is represented by the position of the XY axis and the velocity is expressed as Vx (velocity of the X-axis) and Vy (velocity of Y axis). Therefore, in a PSO algorithm, the best experiences of the groups are always shared with all particles and therefore it is expected that the particles will move towards the better solutions' areas. Each particle knows its best value up to present (P_{best}) and its position XY. Moreover, each particle knows the best value in the group (G_{best}) among the P_{best}. Each particle attempts to modify its position using the current velocity and distance from P_{best} and G_{best}. The modification can be represented by the term of velocity.

In order for the genetic algorithm to apply to the observed optimization problem, it is necessary to define: the goal for a single entity, this single entity is identified as a possible solution to the optimization problem. As described, the genetic algorithm performs targeted search of a part of the space of possible solutions to the observed problem. Certainly, the best solution comes with a full search of a set of solutions. However, for a large number of practical problems, such a method of finding a solution requires too much time due to the complexity of the calculation of the value of the function's function and the over-sized set of possible solutions. When applying a genetic algorithm to a concrete problem, it tries to shorten the running time of the algorithm and obtain a better-quality solution. Although the genetic algorithm, due to its simplicity and a small number of necessary data, makes it appropriate to apply the solution to the problem of optimization, it often does not get satisfactory results because it has the ability to find a global optimum or solution very close but often only provides a local optimum. The genetic algorithm's effectiveness depends largely on the following: adaptation of the algorithm and problem, genetic algorithm (such as population size, iteration number, and encoding mode), breed selection mode and appropriate selection of crossing and mutation genetic operators.

The elements of the genetic algorithm for a specific problem of optimizing the distribution of capacitor batteries are discussed below: minimization of active losses in the power grid, reduction of THD, minimization of operational and construction costs, all with a reduction in voltage reduction. The problem of optimal deployment of existing capacitor-based batteries in the network was discussed.

Usually, in the observed optimization problem, there are different k capacitance batteries. The size-coding is the simplest way to assign the lowest power battery to the number 1, the next number 2, and the battery of the highest power k. The coding of the condenser battery position can also be done in the following, very simple way: first, numeric marking of the possible locations of the (nodes) of the condenser batteries in the network, and then the coding of the battery position is carried out in such a way that the node in which there is no battery is assigned the number 0, and the node in which the battery is located assigns a numeral to the battery size tag (1 or 2 or ... k-1 or k), so that the position of the chromosome numbers corresponds to the numbering of the nodes. An example of a 6 node network is provided for illustrating the coding mode mentioned above, in which three capacitive batteries with rated power 15-defect, 20- defect and 25- defect are to be installed. By encoding the size of the battery, the following codes are given: 1 for a 15-defect battery, 2 for a 20-defect battery, and 3 for a 25-defect battery. Using the described mode of encoding, the size and position of the battery for the network example (Fig. 5.) is obtained in the chromosome of the netting that reads:

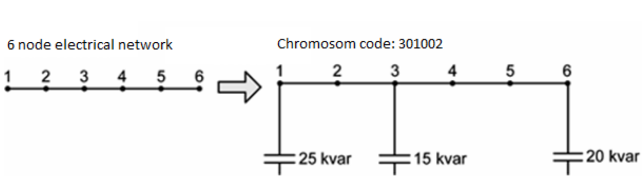


Fig. 5. Chromosome network

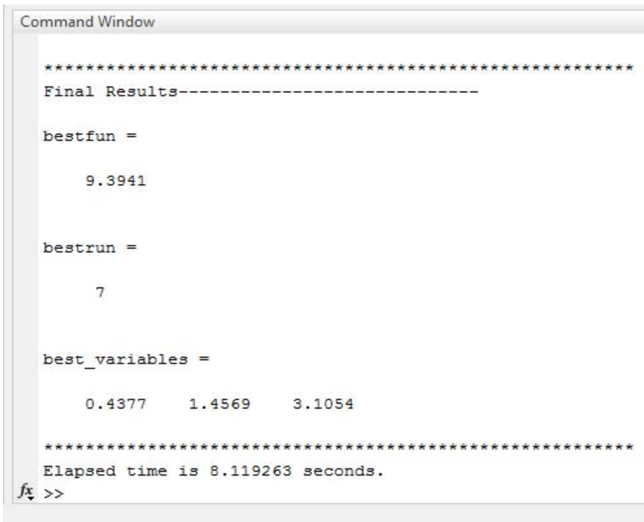
According to this mode, the chromosome of the individual encodes the k + 1 value. Although this rule looks very simple with the numeric code, in the example from Fig. 5. the chromosome of the individual is encoded by a quaternary code, (rather than binary coding), which results in a considerably shorter chromosome in the observed optimization problem. The number of chromosome locations, i.e. the length of the chromosome in this coding mode is equal to the number of network nodes in which the batteries can be incorporated. For networks that, besides the main excerpt, have even sub-items, the node numbering is performed in such a way that they start with the smallest number of nodes at the nearest source and are numbered sequentially with the nodes on the main excerpt. When the end of the main statement is reached, the subtraction of the nearest source etc. is continued.

Here, each gene contains three pieces of data: the node of the gene (determines the position of the gene in the chromosome), the presence of the capacitor battery in the node to which the gene relates (0 - the battery is not connected to the node or a number greater than 0 - the battery is connected to the node) and the size (power) of the battery if it is connected to the node (value greater than 0).

In view of the nature of the observed problem of optimization and the presentation of the encoding method of the individual, this paper proposes a selection type called the selection of the best. The selection of the best subtype is a sorting selection that belongs to a ranking. The reason for choosing this type of selection is the assumption that it will ensure good mixing and presence of most genes in the population.

This assumption is based on the fact that the value of the target function will be approximately equal to two individuals who differ only in the two genes corresponding to adjacent and close nodes in the network. In the genetic algorithms of the goodness of an individual (i.e., how much an individual is good as a problem solution) is determined by the value of the function of the goal. The goodness of a person actually represents the mapping of the function value for individual entities into a new set of values representing values of the goodness of coding mode of the size and location of the condenser batteries of the individual.

An Algorithm has been developed using MATLAB Simulink simulation software, results are the following:



```
Command Window

*************************************************************
Final Results-----------------------------

bestfun =

    9.3941


bestrun =

     7


best_variables =

    0.4377    1.4569    3.1054

*************************************************************
Elapsed time is 8.119263 seconds.
>>
```

Fig. 6. GUI interface of MATLAB Simulink

The simulation can be rated as very fast according to the criterion of duration of convergence process. Optimisation function is presented on Fig. 7.

Some of the main steps in the finding optimal location for facility can be found on block chart flow diagram on Fig. 8.

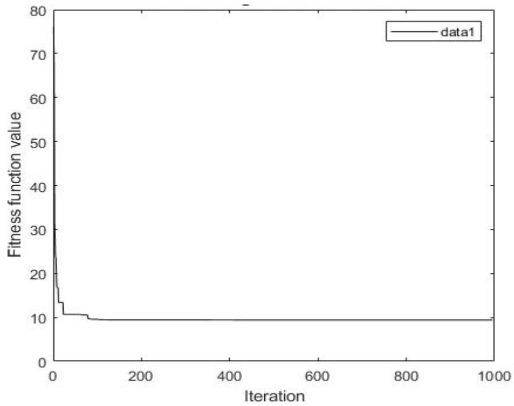


Fig. 7. PSO convergence characteristic

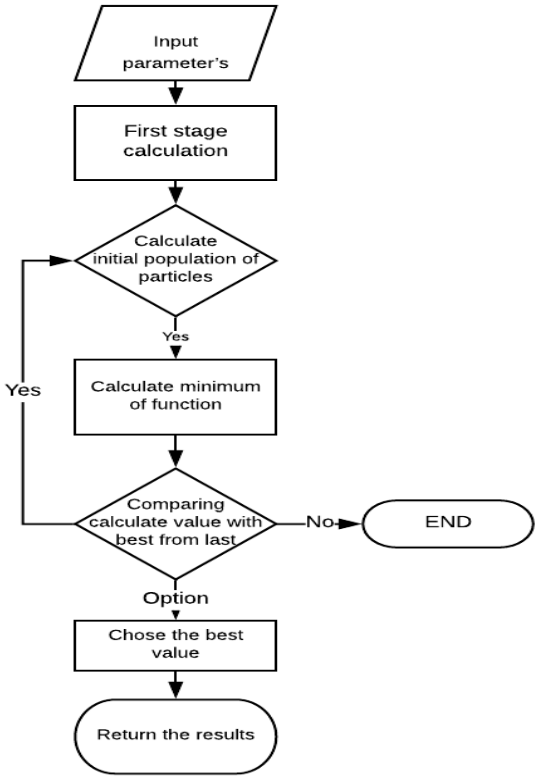


Fig. 8. Block chart flow diagram

For the above given algorithm, adequate program is developed in MATLAB software. In the following text the code for output function is given:

```
tic
clc
clear all
close all
rng default
LB=[0 0 0];
.
fprintf('\n\n');
fprintf('*******************************************
***************\n');
fprintf('Final results of calculation:\n');
[best parametres, best iteration]=min(fff)
Optimal place of embedding =rgbest(best iteration:)
fprintf('*******************************************
***************\n');
```

```
toc
% PSO convergence characteristic
plot(ffmin(1:ffite(best iteration),best iteration),'-k');
xlabel('number of iterations’);
ylabel('value of the Fitness function');
title('PSO optimization curve')
%#############################################
```

Conclusion

The implemented method and algorithm are adequate for solving optimal location-finding problems of CB and their rated power. Discussion and optimisation methods applied in this paper approved of the usage of FACT devices by simulation in the real railway network and real measured values on specific plants also, and argue in favour of this method being of significant importance for the selection of future investments in CB.

Authors: *Josip Pavleka, B.Sc., Engineer at HEP-Distribution System Operator Ltd., Zagreb, Croatia, E-mail: josip.pavleka@gmail.com; Srete Nikolovski, prof.dr.sc., Full Professor at the Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, Croatia, E-mail: srete.nikolovski@ferit.hr; Marinko Stojkov, prof.dr.sc., Full Professor at the Mechanical Engineering Faculty in Slavonski Brod, Croatia, E-mail: marinko.stojkov@sfsb.hr*

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