LODZ UNIVERSITY OF TECHNOLOGY

Faculty of Electrical, Electronic,
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Extended Abstract of PhD Dissertation

Electric Power Losses Reduction in Distribution Systems Using Selective Particle Swarm Optimization

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CONTENTS

1. Introduction

Power losses in distribution networks are a source of economic inefficiency that impacts negatively on the business results of distribution companies. The utilities have to place a high level of importance on improving the efficiency of distribution networks by reducing power losses and improving the voltage profile. One or more of the available techniques for reducing power losses in distribution levels can be employed to achieve significant savings. Benefit/cost ratios can be established to determine which loss reduction techniques are the most suitable for application.

Most of the previous studies dealt with power losses reduction techniques in a separate manner, which may not yield the minimum losses structure of a distribution network. This thesis studies three of power losses reduction techniques: capacitor placement, reconfiguration and reconductoring and their simultaneous application in a large distribution network for finding the optimal structure of this network.

Applying these three techniques to the real large distribution systems simultaneously causes a multi-objective mixed-integer nonlinear programming problem with equality and inequality constraints because not only power losses reduction must be accounted for. There are other important elements in this problem which are: time-varying load and energy losses reduction, limits on bus voltage, voltage harmonic distortion, current-carrying capacity of conductors, practical discrete sizes and node locations of installed capacitors, the nonlinearity of capacitors cost/kvar ratio, distribution network topology has to be radial and power flow constraints are nonlinear in nature.

This work presents a simple modification of the Binary Particle Swarm Optimization to search a decision space. The proposed SPSO is applied in different test systems given in literatures and it is shown that the solutions obtained by the SPSO outperform those obtained by means of other methods proposed in literature. The SPSO is then applied in a real large distribution system to find the optimal capacitor placement, optimal conductor selection and network reconfiguration, the main objectives are to increase the network efficiency by increasing the annual benefits, reducing power and energy losses and improving the voltage profile.

Thesis and objectives

In this work the following thesis is proven:

Applying the modified binary PSO method, which consists of transforming particle coordinates into a selected solution space, makes it possible to effectively solve the problem of minimizing active power losses in a distribution networks by means of the following techniques: capacitor placement, network reconfiguration and reconductoring.

The objectives of this work are:

1. Provide a comprehensive analysis of the different techniques applied to optimize the power losses in the distribution networks by using different test systems and real networks.
2. Develop a simple algorithm for searching in selected spaces that can be used in many engineering applications where the search space consists of specific values.
3. Apply the proposed algorithm to real distribution system for estimating its performance by considering three techniques for power losses reduction separately and simultaneously.
4. Quantitative evaluation of the economic benefits from applying of proposed algorithm in a real distribution network.

To achieve above objectives, the following research has been accomplished and included:

1. Review the techniques proposed by earlier researches in the field of capacitor placement, reconfiguration and reconductoring.
2. Study the effect of harmonics, mutual coupling and unbalance on optimal solution of capacitor placement problem.
3. Apply the proposed algorithm to test systems from the literatures and compare the results to prove its validity and demonstrate its accuracy and the efficiency.

2. Optimization Method

Multi-objective mixed-integer nonlinear programming problems with equality and inequality constraints arise at the using of different techniques for power losses reduction. Many algorithms have been developed to solve these problems starting from the traditional methods up to the modern methods. Traditional methods are intuitive and easy to understand but not efficient in handling these problems for large-scale real networks, especially for cases when search space consists of discrete variables. Most of traditional methods tend to get stuck to a suboptimal solution and often fail to solve optimization problems that have many local optima. Moreover, the convergence of such methods to an optimal solution depends on the chosen optimal solution.

To overcome the drawbacks of traditional methods, the research has been going on during last three decades to identify more effective optimization methods. Most of these methods are based on heuristics and artificial intelligence (AI). AI methods are very flexible and robust tools for solving the complicated optimization problems as compared to traditional methods. One of AI methods is Particle Swarm Optimization (PSO). PSO has received much attention regarding its potential as a global optimization method. The basic version of PSO was intended to handle only nonlinear continuous optimization problems. However, many advances in PSO development elevated its capabilities to handle a wide class of complex engineering and science optimization problems.

PSO was chosen among other AI methods due to its advantages: 1) it is easy to describe and implement; 2) it has a fast convergence speed; 3) it is robust to solve different problems by tuning parameters and the population topology; 4) it is more efficient in maintaining the diversity of potential solutions; 5) it requires less algorithm operators to be adjusted.

Original Version of PSO

The particle swarm optimization algorithm was originally introduced by Kennedy and Eberhart in 1995 [1]. In the algorithm each individual possible solution can be modeled as a particle that moves through the problem hyperspace. Each particle keeps track of its own position and velocity in the problem space. The initial position and velocity of a particle are generated randomly. Each particle in the swarm is iteratively updated according four factors: its current position X_i, its current velocity Vel_i, the best location it has achieved so far, called particle best *(PB)*, and the overall best location achieved by all particles called global best *(GB)*.

PSO is a population-based search-algorithm; the population is called a swarm, the swarm consists of a number of particles that move around in the search space *S*. Suppose that the search space is *d*-dimensional, then:

- Each particle (*i-th* particle) in the swarm is treated as a point in *d*-dimensional space and described as: $X_i = [x_{i1}, x_{i2} \ldots x_{id}]$.
- The set of *n* particle in the swarm is called population and described as: $pop = [X_1, X_2 \ldots X_n]$.
- The best previous position for each particle (the position giving the best fitness value) is called particle best and described as: $PB_i = [pb_{i1}, pb_{i2} \ldots pb_{id}]$.
- The best position among all of the particle best positions achieved so far is called global best and described as: $GB=[gb_1, gb_2 \ldots gb_d]$.
- The rate of position change for each particle is called the particle velocity and described as $Vel_i = [v_{i1}, v_{i2} \ldots v_{id}]$.
- At iteration k the velocity for d-dimension of i-particle is updated by:

$$v_{id}^{k+1} = wv_{id}^{k} + c_1 r_1 (pb_{id}^{k} - x_{id}^{k}) + c_2 r_2 (gb_{d}^{k} - x_{id}^{k}) \tag{1}$$

where, c_1 and c_2 are the acceleration constants, and r_1 and r_2 are two random values in the range [0,1].

- The *i*-particle position is updated by

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \tag{2}$$

Binary PSO

The binary PSO model was presented by Kennedy and Eberhart [2] and is based on a very simple modification of the real-valued PSO. As with the basic PSO a fitness function *F* must be defined. It maps from the *d*-dimensional binary space B^d (i.e. bit strings of length *d*) to the real numbers. In the binary PSO the positions of particles naturally must belong to B^d in order to be evaluated by *F*. This is obtained by applying a sigmoid transformation to the velocity component as in Eqn. (3). It squashes the velocities into a range [0, 1] and force the component values of the particles locations to be 0's or 1's. The equation for updating positions Eqn. (2) is then replaced by Eqn. (4).

$$sigmoid(v_{id}^{k}) = \frac{1}{1+e^{-v_{id}^{k}}} \tag{3}$$

$$x_{id}^{k} = \begin{cases} 1, & if \; rand < sigmoid\left(v_{id}^{k}\right) \\ 0, & otherwise \end{cases} \tag{4}$$

<u>Selective Particle Swarm Optimization (SPSO)</u>

In most engineering applications, optimization problems of continuous or discrete nature arise very often and it may be needed to upgrade the calculated values of variables according to their standard values. Such problems include optimal selection of capacitors for reactive power compensation or optimal selection of conductor cross-sections in distribution networks. Therefore, this thesis proposes a simple modification to the binary PSO to search in a selected space for standard values of capacitor and conductor sizes for which there are minimum power losses in the network. This algorithm is defined here as Selective PSO (SPSO).

In the basic PSO the search space is a real-valued space, where the search space in the binary PSO is a set of *0's* and *1's,* but in the SPSO the search space is a set of selected values. In the SPSO the search space may be different from one dimension to another. For each dimension (for example, *d*-dimension) the search space (S_d) is a set of *dn* values ($S_d = [s_{d1}, s_{d2} \ldots s_{dn}]$), where *dn* is the number of the selected values in the dimension *d*. Similar to the basic PSO and binary PSO, in SPSO the fitness function *F* and the dimensions must be defined. But the difference here is that function *F* maps at each dimension *d* from *dn* values which represent the selective space S_d. By other words, the position of each particle has been changed from being a point in real-valued or binary space to be a point in a selective space. To achieve this change, the sigmoid transformation given in Eqn. (3) has been changed to Eqn. (5), and the *i-th* particle position at a dimension *d* is a selective value, which updated by Eqn. (6)

$$sigmoid(v_{id}^{k+1}) = dn \frac{1}{1+e^{-v_{id}^{k+1}}} \tag{5}$$

$$x_{id}^{k+1} = \begin{cases} s_{d1} & if \quad sigmoid(v_{id}^{k+1}) < 1 \\ s_{d2} & if \quad sigmoid(v_{id}^{k+1}) < 2 \\ s_{d3} & if \quad sigmoid(v_{id}^{k+1}) < 3 \\ . & . \quad . \\ . & . \quad . \\ . & . \quad . \\ s_{dn} & if \quad sigmoid(v_{id}^{k+1}) \leq dn \end{cases} \tag{6}$$

Where, s_{d1}, s_{d2}, s_{d3},....,s_{dn} are the selected values in the dimension d.

Velocity values are restricted to some minimum and maximum values [Vel_{min} , Vel_{max}] using Eqn. (7).

$$v_{id}^{k+1} = \begin{cases} Vel_{\max} & if \quad v_{id}^{k+1} > Vel_{\max} \\ v_{id}^{k+1} & if \quad \left|v_{id}^{k+1}\right| \leq Vel_{\max} \\ Vel_{\min} & if \quad v_{id}^{k+1} < Vel_{\min} \end{cases} \tag{7}$$

To avoid invariability of the velocity value of the particle i at the dimension d at the maximum or the minimum values and to avoid the oscillation of the velocity value of the particle i at the dimension d between the maximum and the minimum values, we use Eqn. (8) to force each particle to go through the search space.

$$v_{id}^{k+1} = \begin{cases} rand * v_{id}^{k+1} & if \quad \left|v_{id}^{k+1}\right| = \left|v_{id}^{k}\right| \\ v_{id}^{k+1} & otherwise \end{cases} \tag{8}$$

As a conclusion for the above, to apply the proposed SPSO to any application the next steps should be followed:

A) Specify the number of dimensions.

B) Find the search space for each dimension.

C) Use SPSO to select the optimal solution from the search spaces for each dimension using equations (1), (7), (8), (5) and (6) respectively.

3. Problem Formulation and Implementation of SPSO for Reducing Losses

In this thesis, SPSO is implemented in different cases for power losses reduction by different techniques, different problem formulation and different assumptions. The results obtained using SPSO are compared with the results obtained using other methods given in literature for each case to investigate the effectiveness of the SPSO. Before starting the implementation, the following item shows load flow and losses analysis.

Load Flow and Losses Analysis

Consider a balanced radial distribution system as shown in Fig. 1, where the general bus *i* contains a load and a shunt capacitor.

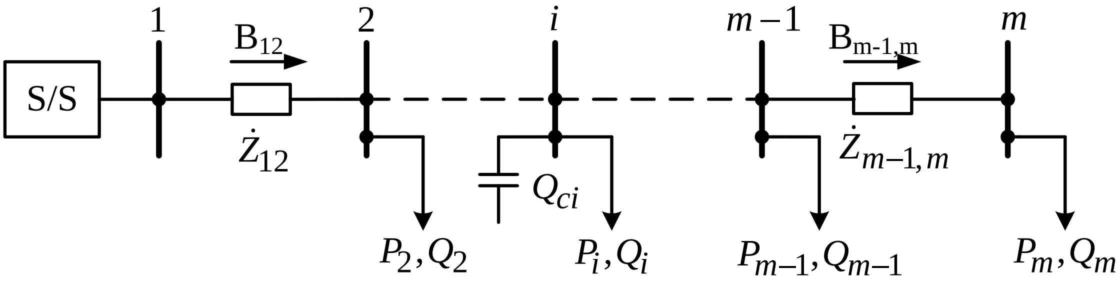

Fig. 1: m-bus radial distribution system

The implementation of fundamental and harmonic load flow and power system analysis can be summarized as follows, [3] and [4]

- Calculate the magnitude and phase angles of the bus voltages at fundamental frequency using the method developed by Teng [5].
- Calculate power losses at fundamental frequency Eqns. (9) and (10).
- Calculate fundamental current, *h-th* harmonic current, *h-th* harmonic frequency load admittances, shunt capacitor admittances and feeder admittances according to Eqns. (11)-(15), respectively.
- Calculate harmonic voltages caused by nonlinear load Eqn. (16).
- Calculate rms voltage and the total harmonic distortion Eqns. (18)-(19) respectively.

$$P_{loss(i,i+1)} = R_{i,i+1}[|V_{i+1} - V_i \| y_{i,i+1}|]^2 \tag{9}$$

$$P_{loss} = \sum_{i=1}^{m} P_{loss(i,i+1)} \tag{10}$$

$$I_i^1 = (P_i - jQ_i)\big/(V_i^1)^* \tag{11}$$

$$I_i^h = w_i I_i^1 \big/ h \tag{12}$$

$$y_{li}^h = (1 - w_i)\left(\frac{P_i}{|V_i^1|^2} - j\frac{Q_i}{h\,|V_i^1|^2}\right) \tag{13}$$

$$y_{ci}^h = h y_{ci}^1 \tag{14}$$

$$y_{i,i+1}^h = \left(R_{i,i+1} + jhX_{i,i+1}\right)^{-1} \tag{15}$$

$$\begin{bmatrix} Y_{11}^h & Y_{12}^h & 0 & & & 0 \\ Y_{21}^h & Y_{22}^h & . & & & \\ 0 & . & . & & & \\ . & & & . & . & 0 \\ . & & & . & Y_{m-1,m-1}^h & Y_{m-1,m}^h \\ 0 & & & 0 & Y_{m,m-1}^h & Y_{m,m}^h \end{bmatrix} \begin{bmatrix} V_1^h \\ V_2^h \\ . \\ . \\ V_{m-1}^h \\ V_m^h \end{bmatrix} = \begin{bmatrix} I_1^h \\ I_2^h \\ . \\ . \\ I_{m-1}^h \\ I_m^h \end{bmatrix} \tag{16}$$

$$Y_{ij}^h = \begin{cases} -y_{ij}^h & if \quad j \neq i \\ y_{i-1,i}^h \quad + y_{i+1,i}^h + y_{li}^h + y_{ci}^h & if \quad j = i \in S_c \end{cases} \tag{17}$$

$$|V_i| = \sqrt{\sum_{h=1}^{H} |V_i^h|^2} \tag{18}$$

$$THD_i(\%) = \frac{100}{|V_i^1|}\sqrt{\sum_{h\neq 1}^{H} |V_i^h|^2} \tag{19}$$

where,

m	the number of buses
$R_{i,i+1}$ and $y_{i,i+1}$	the resistance and admittance of the branch between buses *i* and *i+1* respectively
w_i	the nonlinear portion of the load at *i-th* bus
$(V_i^1)^*$	the complex conjugate of the fundamental voltage at *i-th* bus
P_i, Q_i	load active and reactive powers at *i-th* bus
S_c	the set of candidate buses for shunt capacitor placement
H	the upper limit the harmonic orders being considered
V_i^h	the harmonic voltage at *i-th* bus

By calculating the voltages and admittances for each harmonic order, the harmonic power losses can be calculated using Eqns. (20) and (21).

$$P^h_{loss(i,i+1)} = R_{i,i+1}[|V^h_{i+1} - V^h_i \| y^h_{i,i+1}|]^2 \qquad (20)$$

$$P_{loss} = \sum_{h=1}^{H}(\sum_{i=1}^{m-1} P^h_{loss(i,i+1)}) \qquad (21)$$

Problem Implementation Using SPSO

There are two main requirements before applying the SPSO to any problem which are 1) specifying the number of dimensions, 2) finding the search space for each dimension.

For capacitor placement problem; the number of dimension equals the number of candidate locations. The search space for each dimension is a set of capacitor sizes.

For reconfiguration, to specify the number of dimensions for reconfiguration problem, all tie switches must be closed to give number of loops. The number of dimensions equals the number of loops. The search space for each dimension is a set of the switches which belong to each loop.

For reconductoring, the number of dimension equals the number of candidate branches. The search space for each dimension is a set of standard conductor sizes.

For combination of capacitor placement, reconfiguration and reconductoring, Consider a distribution network consists of m-buses and n-branches with p-loops, the available capacitor sizes are g and the available conductor sizes are b. Therefore, the number of dimensions equals the number of busses plus the number of branches plus the number of loops ($d=m + n + p$). The search space for all the m-dimensions equals g (available capacitor sizes), where the search space for all the n-dimensions equals b (available conductor sizes), but search space for p-dimensions is differ from loop to another as per the number of switches which belong to each loop.

General Problem Formulation

The problems of Capacitor placement, distribution network reconfiguration and reconductoring include many variables such as capacitor type (fixed or switched), capacitor size, capacitor cost, capacitor locations (physical node locations at the feeder to install the capacitor in), branch type (sectionalized switch or tie switch), conductor type, conductor cost … etc. In addition, these problems are subject to some technical and operational constraints.

The following equations represent the general objective function to maximize the profitability from the next distribution systems by means of optimal capacitor placement, distribution network reconfiguration and optimal conductor selection.

$$\text{Minimize} \quad F = K^p P_{loss,1} + \sum_{l=1}^{L} K^e E_{loss,l} + \sum_{b=1}^{Br} K_b^{con} L_b + K^c \tag{22}$$

The first term in equation (22) corresponds to the cost of active power losses, the power losses $P_{loss,1}$ are calculated at the maximum load level using equation (23) considering $l=1$, K^p represents the equivalent annual cost per unit of power losses. $P^h_{loss,l(b)}$ is the *h-th* harmonic power losses at *l-th* load level at the branch *b*; *Br* is the number of branches; *H* is the upper limit of considered harmonic order. The second term in equation (22) corresponds to the cost of energy per year, where the energy losses $E_{loss,l}$ are calculated at the different load levels *l* by (23) and (24), K^e represents the equivalent annual cost per unit of energy losses. *L* is the number of load levels; T_l is the load duration at *l-th* level. The third term represents the conductors cost for all branches *B*, where K_b^{con} is the conductor annual cost/km, L_b is the conductor length in *km*. The forth term represents the capacitors cost calculated by (25), where u^l_{fi} and u^l_{si} are the sizes of fixed and switched type capacitors, respectively, which placed at *l-th* load level and *i-th* bus. k^c_f and k^c_s are the standard capacitor costs for fixed and switched type capacitors, respectively.

$$P_{loss,l} = \sum_{h=1}^{H} \left(\sum_{b=1}^{B} P^h_{loss,l(b)} \right) \tag{23}$$

$$E_{loss,l} = T_l P_{loss,l} \tag{24}$$

$$K^c = \sum_{i \in S_c} \left(k^c_f u^l_{fi} + k^c_s u^l_{si} \right) \tag{25}$$

For each load level, all the following constraints should be achieved .

1. Branch current constraint

$$B_b \leq B_{b\,max} \tag{26}$$

where B_b represents branch *b* current, and $B_{b\,max}$ represents the maximum permissible current of branch *b*. 2.

Node voltage constraint

$$U_{imin} \leq U_i \leq U_{imax} \tag{27}$$

where U_i represents voltage of node *i*, U_{imin} and U_{imax} are minimum and maximum permissible rms voltages of bus *i*, respectively. 3. Harmonic constraint

$$THD_{il} \leq THD_{max} \tag{28}$$

where THD_{il} represents the total harmonic distortion for node *i* at load level *l*, THD_{max} is the maximum allowable total harmonic distortion.

4. VAR constrains

$$\sum_{i=1}^{M} Q_i^c \leq Q_t \tag{29}$$

where $Q^c{}_i$ represents the shunt capacitor size placed at candidate bus *i*, *M* represents the set of candidate buses for capacitor placement, Q_t is the total reactive power demand .

5. Load connectivity

Each bus should be connected via one path to the substation.

6. Radial network structure

This means that no loops are allowed in the network.

<u>Test systems</u>

The SPSO is implemented in different cases for power losses reduction by different techniques, different problem formulation and different assumptions. The results obtained using SPSO are compared with the results obtained using other methods given in literatures for each case to investigate the effectiveness of the SPSO, these methods include heuristic numerical algorithm, exhaustive search, genetic algorithm, branch exchange heuristic method, simulated annealing and ant colony. The general problem formulation and the constraints given above are changed according to the assumptions and the constraints represented in literature for each case.

These cases are summarized in the following.

1. The Effect of Harmonics on Optimal Capacitor Placement and Sizing.
2. Optimal Capacitor Placement in Presence of Harmonics with Time-Variant Load.
3. Optimal Capacitor Placement Considering Mutual Coupling, Load Unbalance and Harmonics.
4. Reconfiguration of the Distribution Systems.

5. Combination of Reconfiguration and Capacitor placement.
6. Combination of Reconductoring and Capacitor placement.

The conclusion of the simulation results obtained from the above cases can be summarized as follows:

- The proposed SPSO is reliable, easy to implement and can be used as an advantageous alternative in the comprehensive optimization for power losses reduction in distribution networks.
- Capacitor placement, distribution network reconfiguration and reconductoring are effective techniques for power losses reduction and voltage profile improvement.
- There are significant differences in results for the same problem when considering different assumptions or different constraints.
- The benefits from capacitor placement when considering harmonics may be less than that when ignoring harmonics, but taking harmonic effect into consideration is more economical because it saves the customers electrical devices.
- Simultaneously considering more than one technique for power loss reduction is more effective than using these techniques separately.

4. Practical Implementation of SPSO

The proposed method is applied to a real network of 274 nodes that covers a zone of the eastern part of the city of Mariupol in Ukraine to find the optimal capacitor placement, optimal conductor selection and network reconfiguration. The main objectives are to increase the network efficiency by increasing the annual benefits, reducing power and energy losses and improving the voltage profile. Fig. 2 shows the simplified single line diagram of 6 kV network. The network consists of 37 feeders feed from three substations, these feeders contains 274 buses and 284 branches, 273 of the branches are normally closed (sectionalizing switches) and 11 are normally opened (tie switches).

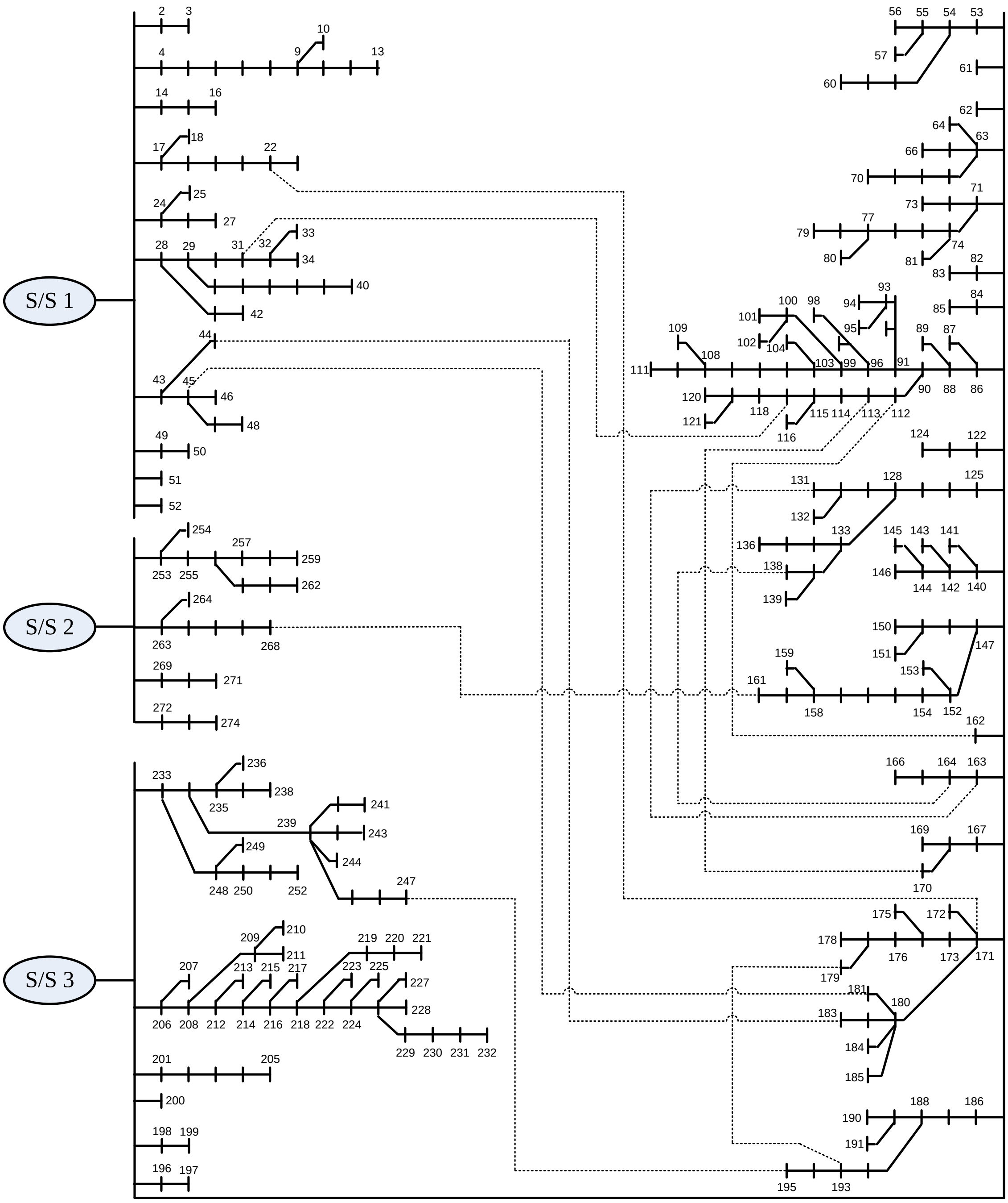

Fig. 2: Simplified single line diagram of 6 kV practical distribution network supplying the eastern part of city Mariupol, Ukraine

The following main data and assumptions are based on the measurements on four feeders with highest power losses and voltage drop in the real network.

- The system is three-phase balanced system.
- The base voltage is 6 kV, whereas the three substations voltage magnitudes are set to 6.35 kV (about 1.06 p.u.).

- Three load levels are represented as a percentage of the transformers ratings at each load point. These percentages are 26%, 49% and 91% for light, medium and heavy load levels, respectively.
- The time period T representing the number of hours in one year (8760 hours) is divided into three intervals for three load levels. These intervals are 1752, 5256 and 1752 hours for light, medium and heavy load levels, respectively.
- The power factor = 0.85.
- Harmonic generation is solely from the substation voltage supply. The substation voltage contains 1.5%, 3.5% and 1.5% of *3-rd*, *5-th* and *7-th* harmonic, respectively, resulting in a total harmonic distortion of *3.9%.*
- The mutual coupling is ignored.
- There are eight branches in the single line diagram of unknown data. The resistance per km, reactance per km and the length in km for these branches are assumed to be 0.125, 0.071 and 1 respectively .
- The candidate branches for reconductoring are 258 of the total 284 branches. The remaining branches (26 branches) are: 11 tie branches, 8 without data (as indicated above) and 7 have a very small length .
- All the branches for any loop act as candidate branch for reconfiguration.
- Smallest capacitor size is Q_{c0}=50 kvar, the maximum capacitor size is Q_{cmax}= 800 kvar. The switched type capacitors are assumed to be with 50 kvar step.
- Tables 1, 2 and 3 give the costs per kvar for the capacitor sizes and the complete data for conductors (cables and overhead lines), respectively. The prices in these tables assume 10 years lifetime for the capacitors and the conductors.
- The cost per unit of power and energy losses are K^p = 168 \$/kW and K^e = 0.035 \$/kWh .

Table 1: Costs per kvar for the capacitor sizes which used in the simulations

size (kvar)	50	100	150	200	250	300	350	400
Cost ($/kvar)	2.25	1.78	1.93	1.44	1.60	1.33	1.46	1.24
size (kvar)	450	500	550	600	650	700	750	800
Cost ($/kvar)	1.35	1.19	1.28	1.13	1.22	1.22	1.29	1.09

Table 2: Cables data

	Conductor size	R (Ohm/km)	X (Ohm/km)	Price for 1of 10 years ($/km)	Maximum allowable current I_{max} (A)
1	3x70	0.443	0.08	1000	180
2	3x95	0.32	0.078	1237.5	213
3	3x120	0.253	0.076	1412.5	243
4	3x150	0.206	0.074	1637.5	275
5	3x185	0.164	0.073	1900	307
6	3x240	0.125	0.071	2350	351

Table 3: Overhead lines data

	Conductor size	R (Ohm/km)	X (Ohm/km)	Price for 1of 10 years ($/km)	Maximum allowable current I_{max} (A)
1	ACK-35	0.9	0.4	187.5	175
2	ACK-50	0.65	0.39	250	210
3	ACK-70	0.46	0.38	350	265
4	ACK-95	0.33	0.37	487.5	330
5	ACK-120	0.27	0.36	725	390
6	ACK-150	0.21	0.35	825	450

Implementation of SPSO

Capacitor placement, network reconfiguration and reconductoring are considered as three problems, even though they are united in one problem. Each problem has its own dimensions and search spaces as described in the following:

For capacitor placement, the number of dimensions equals the number of candidate buses for capacitor placement. In this work the candidate buses are identified by fuzzy expert system (FES) as given in [6] and [7]. The candidate buses chosen by fuzzy set theory are 60 buses, therefore the number of dimensions for capacitor placement problem (d_{cp}) will be 60 . The search space for each dimension is a set of standard capacitor sizes. From Table 1, the search space for each of the d_{cp}-dimensions (S_{dcp}) are the set of 16 capacitor standard values, S_{dcp}=[50 100 150 ….. 800].

For reconfiguration, the number of dimensions equals the number of loops. In this case the number of dimensions for reconfiguration (d_{rf}) is 11.

All tie and sectionalizing switches which belong to any loop are considered as candidate switches for reconfiguration problem. The network could be simplified by taken into account the branches which belongs to each loop only. Fig. 3 shows the 11 loops, from these loops the search space could be identified as follows:

S_{drf1}=[85 87 89 111 274 161];

S_{drf2}=[112 275 169 167 166 274 161];

S_{drf3}=[113 114 116 276 30 29 28 27];

S_{drf4}=[16 18 19 20 21 277 170];

S_{drf5}=[180 278 44 43 279 182 181];

S_{drf6}=[179 42 170 43 279 182 181];

S_{drf7}=[172 173 175 176 178 280 185 186 191 192];

S_{drf8}=[193 194 281 246 245 244 238 233 232 185 186 191 192];

S_{drf9}=[124 125 126 127 162 132 136 137 282 161];

S_{drf10}=[128 129 131 283 132 136 137 282 161];

S_{drf11}=[146 151 153 154 155 156 157 159 160 284 267 266 265 264 262];

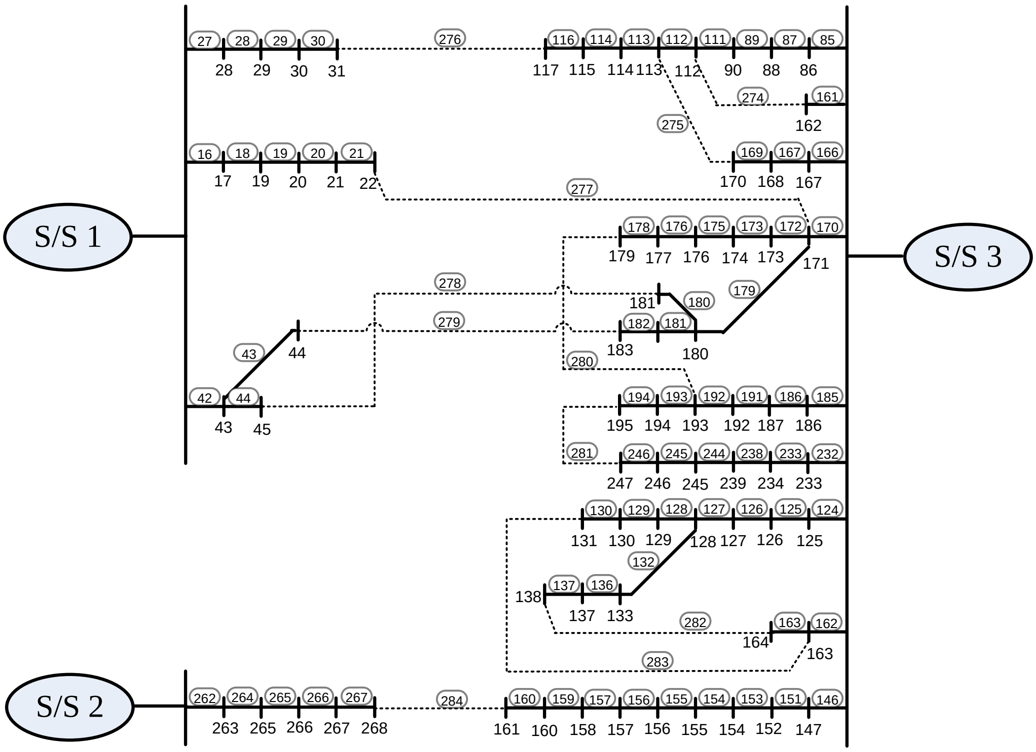

Fig. 3: loops for reconfiguration

For reconductoring, candidate branches for reconductoring are 258 of the total 284 branches (169 of these branches are cables and 89 are overhead lines). The number of dimensions equals the number of candidate branches for reconductoring. There are two numbers of dimensions: one for cables and the other one for OHL, as follows:

- The number of dimensions for cable branches (d_{rcc}) is 169; the search space for these dimensions is a set of 6 cable sizes as given in Table 2.

- The number of dimensions for OHL branches (d_{rco}) is 89; the search space for these dimensions is a set of 6 OHL sizes as given in Table 3.

Using SPSO to select the optimal solution, upon the above, when uniting the three problems (capacitor placement, network reconfiguration and reconductoring), the number of dimension (d) will be 329 ($d=d_{rf}+d_{cp}+d_{rcc}+d_{rco}$). After specifying the number of dimensions and finding the search space for each dimension, SPSO would be applied to select the optimal solution from the search space for each dimension using equations (1), (7), (8), (5) and (6) respectively. Fig. 4 shows flow chart for the proposed method.

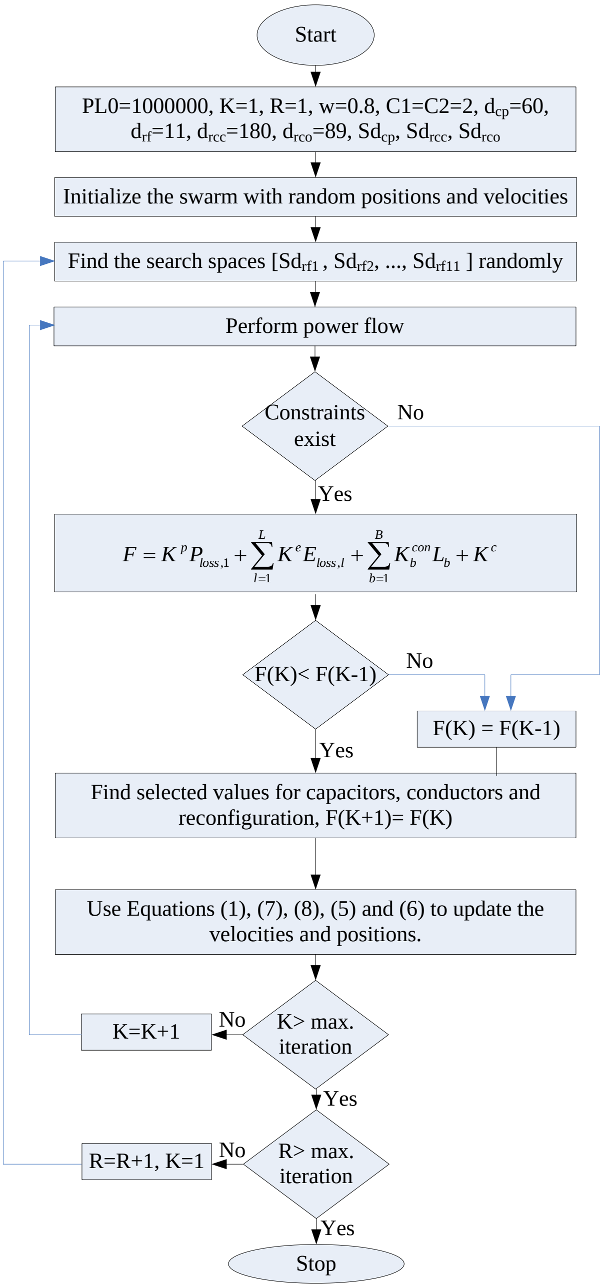

Fig. 4: Flow chart for the proposed method

The simulation carried out with multiple runs using “MATLAB R2010a” as a claculation tool to get the optimal results. The best results were achieved for the coefficient values $c_1 = c_2 = 2.0$, w =0.8, Vel_{max} = 4 and Vel_{min} = -4 and a swarm size of 500 particles. The main objectives herein could be summarized as follows:

1. Verify the effectiveness of the proposed method.
2. Show the efficiency of different techniques for reducing losses and improve the voltage profile.
3. Compare the results obtained by uniting all techniques in one problem, with the results obtained by applying these techniques separately .
4. Demonstrate the effect of considering harmonics on the optimization problem.
5. Quantitative evaluation of economic benefits obtained from applying different techniques for losses reduction.

To achieve these objectives, the problem is posed as an optimization problem with main objective to increase the total benefits from the distribution network by reducing the total losses and improving the voltage profile assuming the following different cases:

A. Considering optimal capacitor placement only
B. Considering reconductoring only
C. Considering reconfiguration only
D. Considering all techniques (capacitor placement, reconductoring and reconfiguration) without THD constraint
E. Considering all techniques (capacitor placement, reconductoring and reconfiguration) with THD constraint

The objective function and constraints that mentioned in sections 3 above are used as general formulas. For the different cases the objective function and constraints should be modified according to the requirements for each case. Table 4 shows the objective functions and constraints for each case, where the constraints numbers are:

1. Branch current constraint, Eqn. (26).
2. Node voltage constraint, Eqn. (27).
3. Harmonic constraint, Eqn. (28).
4. VAR constrains, Eqn. (29).
5. Load connectivity.
6. Radial network structure.

Table 4: The objective functions and constraints for different cases

	Objective Function	Constraint no.					
		1	2	3	4	5	6
Case A	$F = K^p P_{loss,1} + \sum_{l=1}^{L} K^e E_{loss,l} + K^c$	N	Y	N	Y	N	N
Case B	$F = K^p P_{loss,1} + \sum_{l=1}^{L} K^e E_{loss,l} + \sum_{b=1}^{Br} K_b^{con} L_b$	Y	N	N	N	N	N
Case C	$F = K^p P_{loss,1} + \sum_{l=1}^{L} K^e E_{loss,l}$	Y	N	N	N	Y	Y
Case D	$F = K^p P_{loss,1} + \sum_{l=1}^{L} K^e E_{loss,l} + \sum_{b=1}^{Br} K_b^{con} L_b + K^c$	Y	Y	N	Y	Y	Y
Case E	$F = K^p P_{loss,1} + \sum_{l=1}^{L} K^e E_{loss,l} + \sum_{b=1}^{Br} K_b^{con} L_b + K^c$	Y	Y	Y	Y	Y	Y

Y: means this constraint has been applied in this case.

N: means this constraint has not been applied in this case.

Simulation Results and Discussions

The maximum power, total energy and losses of both power and energy at different load levels before optimization are shown in Table 5. The maximum demand for the present network is 62924.23 kW, 7.4% of this demand represents the losses in the conductors. The annual energy delivered by the network at the three load levels is 15853463.9 kwh, 5% of this energy lost in the conductors.

Table 5: State of the network before optimization

Load Level	Light	Medium	Heavy
Percentage of load to transformers ratings	0.26%	0.49%	0.91%
Power factor	0.85		
Total power (kw)	17978.35	33882.28	62924.23
Load level period (hours/year)	1752	5256	1752
Total energy (kwh)	31498069.2	178085237	110243242.2
Total energy per year (kwh)	319826548.4		
Power losses (kw)	378.52	1344.43	4636.98 (7.4%)
Energy losses (kwh)	663159.9	7066315.8	8123988.2
Total energy losses per year (kwh)	15853463.9 (5%)		

Figs. 5, 6 and 7 show the optimal capacitor placement for cases A, D, and E respectively. Tables 6 and 7 give the optimal conductor sizing for cables and OHL, respectively for different cases. Table 8 shows optimal network configuration for the deferent cases.

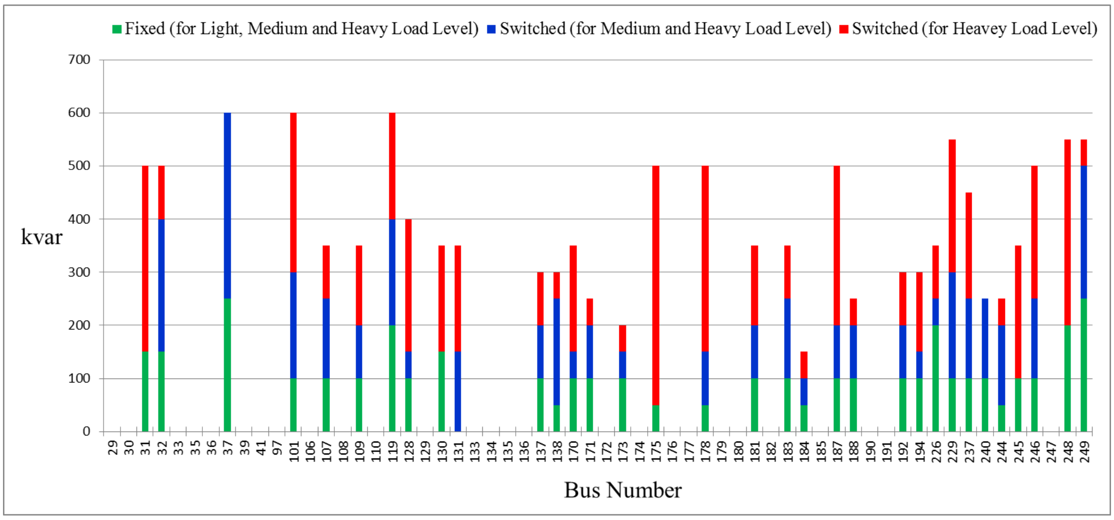

Fig. 5: Capacitor placement and sizing for Case A

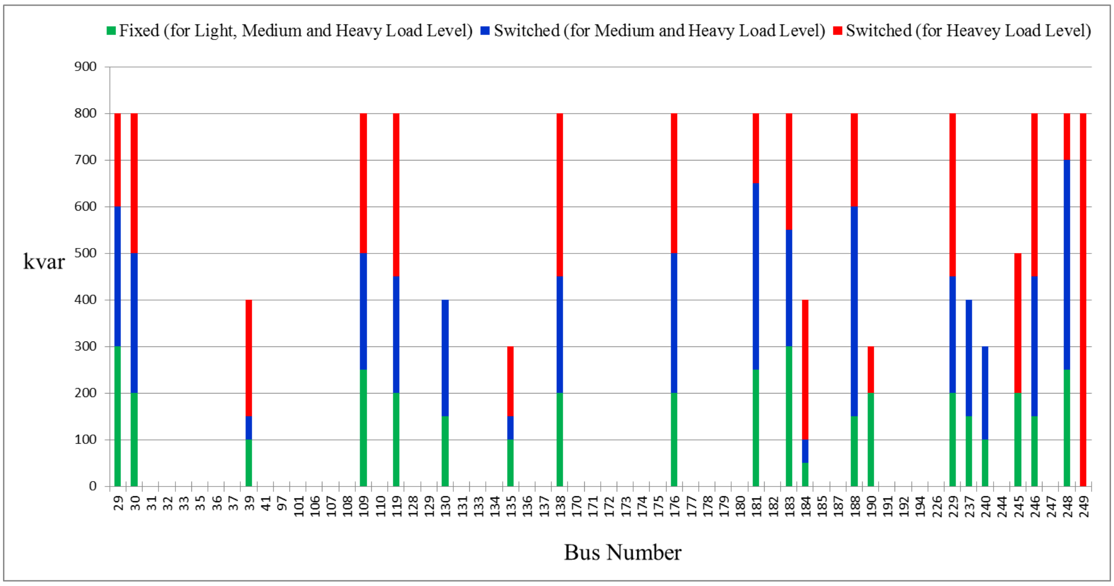

Fig. 6: Capacitor placement and sizing for Case D

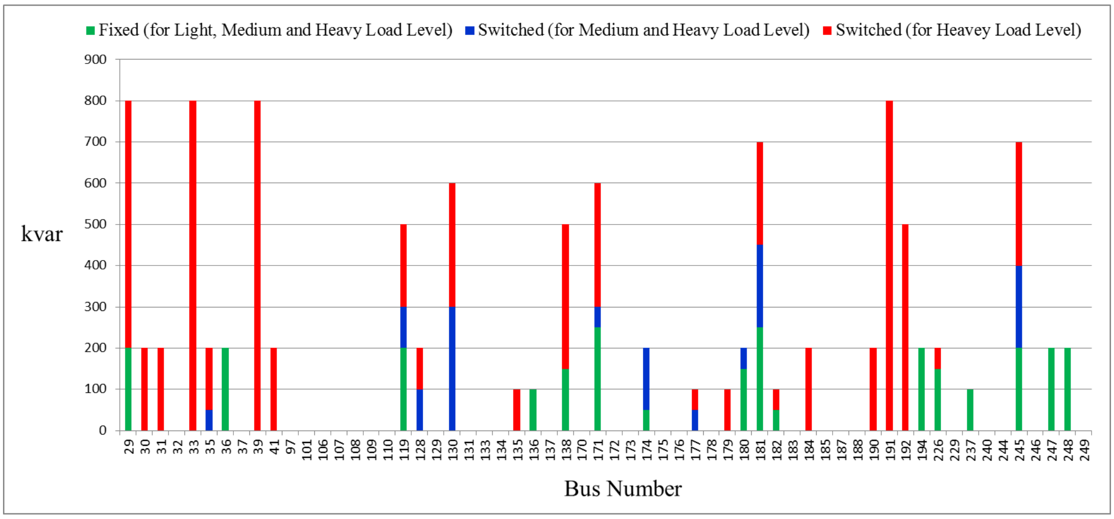

Fig. 7: Capacitor placement and sizing for Case E

Table 6: Cable sizing

Cable Size	Base Case	Case B	Case D	Case E
1	36, 52, 54, 57, 64, 65, 68, 71, 72, 80, 113, 133, 152, 173, 204, 235, 239, 241	41, 47, 50, 51, 65, 80, 84, 121, 122, 123, 131, 145, 161, 171, 180, 182,183, 189, 195, 197, 235, 236, 237, 243, 253, 261, 263, 267	41, 47, 50, 51, 63, 65, 80, 84, 121, 122, 123, 130, 131, 138, 145, 156, 171, 180, 182, 183, 189, 195, 197, 199, 235, 236, 237, 243, 253, 261, 263	47, 50, 51, 63, 65, 80, 84, 91, 108, 121, 122, 123, 131, 135, 136, 138, 145, 156, 171, 173, 180, 183, 184, 195, 197, 199, 235, 237, 240, 243, 244, 246, 248, 251, 253, 261, 263
2	28, 30, 33, 58, 66, 67, 69, 73, 74, 75, 76, 117, 118, 123, 134, 135, 136, 153, 154, 156, 157, 159, 160, 164, 167, 172, 182, 184, 188, 189, 192, 193, 194, 234, 236, 237, 240, 245, 246, 250, 251, 254, 255, 256,257, 259, 260, 261, 266, 267	9, 12, 17, 26, 43, 58, 59, 68, 69, 78, 82, 91, 108, 130, 135, 137, 152, 165, 184, 190,194, 240, 246, 248, 251	9, 12, 17, 26, 55, 58, 59, 68, 69, 78, 79, 82, 91, 108, 135, 136, 152, 158, 165, 168, 184, 190, 240, 246, 248, 251	9, 12, 17, 26, 32, 33, 55, 58, 59, 68, 69, 78, 79, 82, 130, 134, 137, 152, 158, 165, 168, 172, 181, 182, 189, 190, 236, 239, 241, 245, 250
3	2, 6, 8, 9, 11,12, 14, 15, 18, 20, 22, 26, 32, 43, 44, 45, 46, 47, 49, 78, 84, 91, 121, 122, 129, 130, 131, 137, 145,147, 148, 165, 166, 171, 179, 180, 181, 183, 190, 201, 202 , 243, 244, 248, 249, 264, 272	2, 14, 15, 24, 25, 32, 33, 45, 46, 57, 61, 64, 72, 118,129, 133, 134, 136, 181, 202, 204, 234, 239, 241, 250, 260, 265, 266	2, 14, 15, 22, 24, 25, 32, 33, 45, 46, 57, 61, 64, 72, 118, 129, 133, 134, 181, 194, 202, 204, 234, 239, 241, 250, 260	2, 14, 15, 22, 24, 25, 41, 45, 46, 57, 61, 64, 72, 116, 117, 118, 133, 193, 194, 202, 204, 234, 249, 260
4	4, 5, 19, 25, 61, 82, 161, 271	1, 11, 20, 22, 36, 49, 67, 71, 75, 76, 117,147, 148, 159, 160, 164, 166, 167, 173, 188, 192, 193, 201, 245, 257, 259, 264, 272	1, 11, 35, 36, 49, 67, 71, 75, 76, 77, 117, 137, 147, 148, 154, 159, 164, 166, 167, 172, 173, 179, 188, 192, 193, 201, 245, 257, 259, 272	1, 11, 36, 49, 67, 71, 75, 76, 77, 129, 147, 148, 154, 159, 164, 166, 167, 187, 188, 201, 257, 259, 272
5	10, 17, 24, 41, 48, 62, 70, 108, 139, 186, 232, 233, 238, 247, 252, 253, 262, 263, 265	10, 18, 19, 30, 44, 54, 66, 74, 113, 139, 172, 256, 244, 249, 262, 271	10, 30, 43, 54, 66, 74, 113, 116, 124, 139, 160, 187, 200, 244, 249, 256, 271	10, 30, 35, 43, 54, 66, 74, 113, 124, 139, 160, 200, 238, 256, 271
6	1, 3, 16, 23, 50, 51 , 59, 195, 197	3, 4, 5, 6, 8, 16, 23, 28, 48, 52, 62, 70, 73, 153, 154, 156, 157, 179, 186, 232, 233, 238, 247, 252, 254, 255	3, 4, 5, 6, 8, 16, 18, 19, 20, 21, 23, 28, 42, 44, 48, 52, 62, 70, 73, 85, 146, 153, 157, 161, 162, 186, 232, 233, 238, 247, 252, 254, 255, 262, 264, 265, 266,267	3, 4, 5, 6, 8, 16, 18, 19, 20, 21, 23, 28, 42, 44, 48, 52, 62, 70, 73, 85, 146, 153, 157, 161, 162, 179, 186, 192, 232, 233, 247, 252, 254, 255, 262, 264, 265, 266, 267

Table 7: OHL sizing

OHL Size	Base Case	Case B	Case D	Case E
1	29, 34, 38, 39, 120,127, 128, 132, 174,175, 176, 177, 178, 229, 230, 231, 258, 273	94, 96, 140, 142, 149, 150, 177, 210, 226	94, 96, 127, 140, 142, 149, 150, 177, 210, 226	88, 93, 94, 96, 97, 100, 101, 103, 110, 115, 120, 140, 142, 149, 150, 176, 177, 178, 206, 214, 224, 226, 227, 231, 242
2	13, 37, 86, 88, 90, 92, 93, 94, 95, 96, 98, 100, 101, 102, 103, 104, 105, 106, 107, 109, 110, 115, 119, 140, 142, 144, 149, 150, 206, 219, 220, 222, 226, 228	56, 83, 88, 93, 97, 100, 101, 103, 110, 115, 120, 169, 174, 178, 206, 209, 212, 214, 216, 220, 222, 224, 227, 231, 242, 258	56, 83, 88, 93, 97, 100, 101, 103, 110, 115, 120, 169, 174, 178, 206, 209, 212, 214, 216, 220, 222, 224, 227, 231, 242,258	56, 83, 86, 92, 109, 119, 127, 128, 169, 174, 175, 209, 210, 212, 216, 222, 230, 258
3	40, 56, 87, 89, 97, 111, 112, 114, 125, 141, 143, 169, 170, 208, 209, 210, 212, 213, 214, 216, 221,242	39, 40, 92, 109, 119, 143, 144, 273	39, 40, 92, 109, 119, 143, 144, 273	39, 40, 132, 143, 144, 219, 220, 229, 273
4	27, 81, 83,185, 207, 211, 215, 217, 218, 224	37, 38, 86, 106, 107, 141, 175, 176, 208, 218, 219, 229, 230	37, 38, 86, 106, 107, 126, 141, 175, 176, 208, 218, 219, 229, 230	37, 38, 126, 141, 208, 218, 228
5	227	104, 105, 128, 228	104, 105, 128,228	.-------
6	223, 225	13, 27, 29, 34, 81, 87, 89, 90, 95, 98, 102, 111, 112, 114, 125, 126, 127, 132, 170, 185, 191, 207, 211, 213, 215, 217, 221, 223, 225	13, 27, 29, 34, 81, 87, 89, 90, 95, 98, 102, 111, 112, 114, 125, 132, 170, 185, 191, 207, 211, 213, 215, 217, 221, 223, 225	13, 27, 29, 34, 81, 87, 89, 90, 95, 98, 102, 104, 105, 106, 107, 111, 112, 114, 125, 170, 185, 191, 207, 211, 213, 215, 217, 221, 223, 225

Table 8: Reconfiguration results for different cases

	Opened branches
Base Case	274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284
Case C	111, 275, 276, 170, 278, 181, 178, 281, 132, 129, 157
Case D	111, 275, 276, 170,181, 179, 178, 245, 132, 129, 157
Case E	111, 275, 276, 170,181, 179, 178, 245, 132, 129, 157

The simulation results for the different cases at the different load levels are presented in Table 5.11.

Table 9: Simulation results

	Case Number					
	Base case	A	B	C	D	E
Total capacitor [kvar]	0	13000	0	0	13400	10700
Min. voltage[pu]	0.79	0.9	0.893	0.878	0.977	0.96
Max. voltage[pu]	1.06	1.06	1.06	1.06	1.06	1.06
Max. THD [%]	3.9	9	3.9	3.9	8.5	4.99
Power losses [kW]	4637.0	3804.6	2691.2	3902.2	2095.9	2211.0
Energy losses per year [kWh]	15853464	13016471	9200991.4	13341410	7166639	7600738
Power losses [%]	7.4	6	4.3	6.2	3.3	3.5
Energy losses [%]	5	4	2.9	4.2	2.24	2.38

From the above tables and figures several points can be observed as follows.

- Despite fuzzy choice of 60 buses for capacitor placement, SPSO reduced these placements to 33, 21 and 31 buses for cases A, D and E respectively. Therefore SPSO not only find the optimal sizing but also the optimal placement.
- After optimization by deferent techniques, the voltage profile improved to acceptable values. The best improvement of the voltage profile is obtained in cases D and E.
- Before optimization, the maximum THD is under the maximum permissible level.
- In cases B and C, the maximum THD is not affected. But in cases A, D and E when the capacitors exist, the THD is affected based on the capacitors location and sizes.
- In cases A and D when no limits on THD (ignoring THD constraint), the maximum THD raised over the limit (5%).
- Putting constraint to the maximum THD in case E, force the values of THD at each bus to be under the maximum permissible limit at different load levels .
- Case B gives the maximum losses reduction comparing to cases A and C.
- Cases D and E, when considering the three losses reduction techniques at the same time, give the best results.

- The percentages of power losses reduction for all cases are higher than that for energy losses reduction.
- Despite Case D gives the best losses reductions, Case E remains the best choice because it keeps the quality of the delivered power by placing the THD under the permissible limits.

Economic Evaluation

The benefits from power losses reduction are obtained from the savings produced by the avoided costs due to investment deferral in the expansion of the network. In other words, reducing the power losses means reducing the capital cost of the network. On the other hand reducing the energy losses at different load levels means reducing the running cost of the network.

Table 10 and Fig. 8 show the cost of power losses, energy losses, installed capacitors and installed conductors for different cases. Table 11 shows the annual benefits for different cases resulting from power and energy losses reduction. Cases D and E give the least total cost among all the cases. When comparing the results obtained by the three techniques of losses reduction separately (Cases A, B and C), it can be concluded that

- The maximum cost of power and energy losses is obtained in Case C. where the minimum cost of power and energy losses is obtained in Case B.
- Despite there are no installation cost in Case C, the total costs in this case are still maximum. That is is because Case C gives the minimum losses reduction.
- The cost of the conductors is much higher than the cost of capacitors; it represents almost 12 times the cost of capacitors.
- Based on the input data of K^p and K^e, the cost of power losses is about 1.4 times the cost of energy losses for one year.

Table 10: Cost of power losses, energy losses, installed capacitors and installed conductors for different cases

	Case Number					
	Base case	A	B	C	D	E
Power losses cost [$/year]	779012.57	639170.44	452122.46	655577.8	352113	371453
Energy losses cost [$/year]	554871.24	455576.5	322034.7	466949.3	250832	266026
Capacitor cost [$/year]	0	17213.3	0	0	17521.5	13421.3
Conductor cost [$/year]	0	0	213736	0	210827	206432

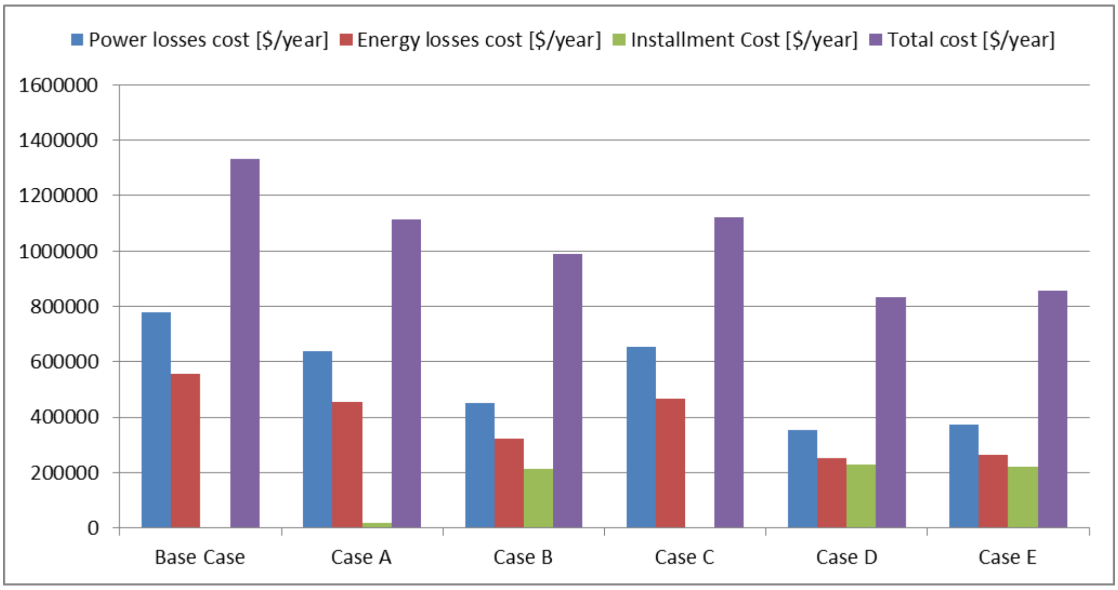

Fig. 8: Costs for different cases

Table 11: total benefits

	Case Number					
	Base case	A	B	C	D	E
Total cost [$/year]	1333883.8	1111960.2	987893.5	1122527	831294	857332
Benefits [$/year]	0	221923.6	345990.4	211356.6	502590	476552
Benefits [%]	0	16.6	25.9	15.8	37.7	35.7

Payback period for different cases

The lifetime of the capacitors and the conductors is 10 years as per the assumptions above. Table 12 shows the payback period for the different cases considering both power and energy losses reduction.

- Case B gives the longest payback period (3.82 years), whereas the payback period for Case C is zero because there is no any initial cost. This means the noticeable benefits started immediately when applying Case C to the network.
- Despite that the payback period for Case B is very long (3.82 years) comparing to Cases A and C, but total saving in the remaining period for Case B is more than that for the other two cases as shown in Table 13.
- The maximum benefits in the 10 years given by Case D which is about 50 million dollars as shown in Fig. 9. But still Case E is the best choice where it gives more than 47 million dollars as 10 years benefits with higher power quality.

Table 12: Payback period for different cases

	Case Number				
	A	B	C	D	E
Capacitors cost [$]	172132.5	0	0	175215	134212.5
Conductors cost [$]	0	2137363	0	2108270	2064316.4
Investments cost (for 10 years) [$]	172132.5	2137363	0	2283485	2198528.9
Power saving per year	832.39	1945.77	734.73	2541.07	2425.95
Energy saving per year	2836992.88	6652472.56	2512054.27	8686825.28	8252726.35
Power saving per year in dollars [$]	139842.131	326890.11	123434.72	426899.51	407559.226
Energy saving per year in dollars [$]	99294.75	232836.54	87921.90	304038.88	288845.42
Annual Saving ($/year)	239136.88	559726.65	211356.62	730938.40	696404.65
Payback period (year)	0.72	3.82	0.00	3.12	3.16

Table 13: Total saving in the remaining period

	Case Number				
	A	B	C	D	E
The remaining period (year)	9.28	6.18	10.00	6.88	6.84
Total saving in the remaining period ($)	2219236.31	3459903.5	2113566.2	5025898.7	4765517.61

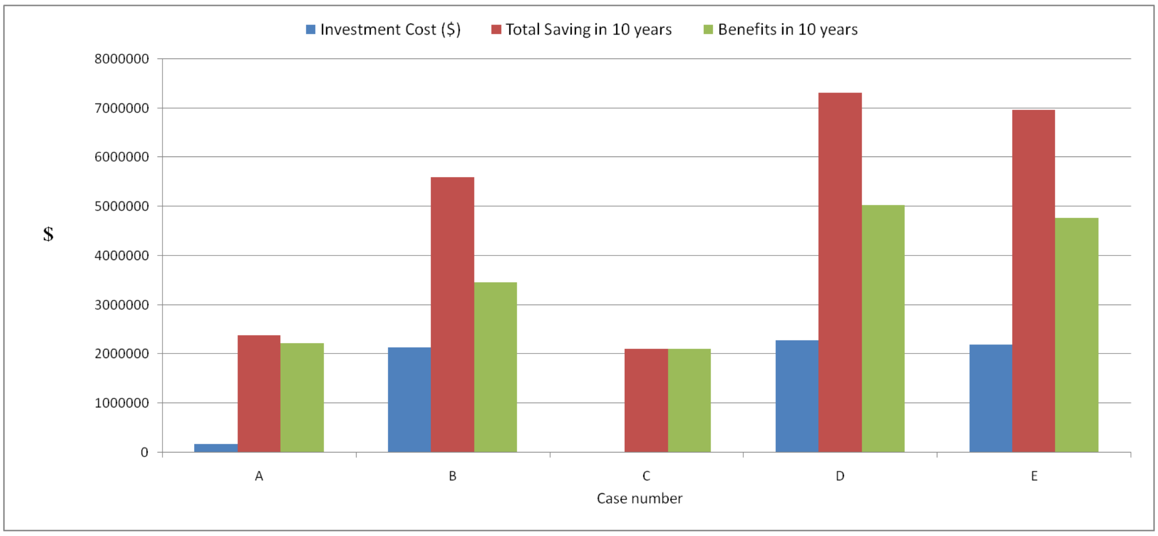

Fig. 9: Total benefits in 10 years

5. Conclusions

It became comprehensible throughout this thesis that there were two main issues involved in the loss reduction problem. The first issue was the power losses reduction techniques with their technical and operational constraints, while the second and equally-important issue was the efficient optimization method. The optimal solution for the problems of capacitor placement, reconductoring and reconfiguration offers utilities the opportunity to reduce energy costs and capital cost as well as release existing system capacity. These techniques can be applied in distribution systems to achieve economic and operational benefits. The achievement of such benefits depends mainly on the optimal choice of capacitor location, capacitor type, capacitor size, conductor size and tie switches. The optimization procedure to solve these problems is subject to some technical (maximum permissible branch current, maximum and minimum voltage limits, maximum THD limit and maximum permissible size of capacitors) and operational (load connectivity and radial network structure) constraints.

An overview of optimization methods are presented in this work by introducing a definition of optimization and classification of the optimization methods to traditional and modern. A comprehensive overview of PSO is given; this overview includes the structure of PSO and its advantages over other similar optimization methods. The original PSO is presented with its own parameters and implementation procedure. Then the different extensions to the original PSO and the selection of its parameters were discussed. Finally, the proposed variant of PSO was presented with its formulas.

Selective particle swarm optimization (SPSO) as a simple modification of the binary PSO searching in the specific decision space is developed in this work and proposed to solve a multi-objective mixed-integer nonlinear optimization problems with equality and inequality constraints. It is shown that SPSO can be used as an engineering practice optimization algorithm, and is suitable for combining the capacitor placement and sizing, reconfiguration and reconductoring techniques to reduce power losses in the distribution systems more effectively. Proposed algorithm can be easily realized in only few tens lines by means of any high-level programming language with low computational time Low algorithmic complexity favors the employment of SPSO in practical real- applications.

SPSO is implemented in different test systems presented in the literature for power loss reduction to investigate the effectiveness of SPSO comparing to traditional and other modern methods. The simulation results obtained by SPSO are better than or the same as the other methods which means that SPSO can be used as an advantageous alternative in the comprehensive optimization for power loss reduction in distribution networks.

SPSO is applied to 6 kV practical distribution network with 274 buses and 284 branches that supplies the eastern part of Mariupol city in Ukraine. It was assumed that the three techniques of losses reduction were applied symultaneously to demonstrate maximum technical and economical benefits that can be achieved. Furthermore, the impact of each of the three techniques on the losses reduction were assessed demontrated, as well as their influence on the financial return were evaluated .

Before starting simulation of practical distribution system, the field measurements on four feeders with highest power losses and voltage drop were made by Fluke 435 power quality analyzer to approve main data and assumptions.

A two-stage approach uniting the fuzzy expert system and SPSO was developed and realized in MATLAB to select the optimal capacitor placement and sizing for the real network .

The effectiveness of SPSO to realize the simultaneous capacitor placement and sizing, reconfiguration and reconductoring has been illustrated by the positive economic response after optimization, in addition to keeping the maximum THD within prescribed level and improving the voltage profile at the same time. The payback period would be 3.16 year and the total saving for all project is equal to $4765517.61 at the $2198528.9 investment cost (for 10 years) and $696404.65 annual saving when considering the cost of both power and energy losses reduction under harmonic conditions.

In this way the thesis “Applying the modified binary PSO method, which consists of transforming particle coordinates into a selected solution space, makes it possible to effectively solve the problem of minimizing active power losses in a distribution networks by means of the following techniques: capacitor placement, network reconfiguration and reconductoring” are proved.

The most important goals achieved throughout the work are:

1. Comparison of the optimization methods used in electrical power engineering.
2. Development of SPSO.
3. Prove the validity of SPSO and demonstrate its accuracy and the efficiency comparing to traditional and other modern methods.
4. Application of SPSO for solving the problem of optimal loss reduction in real distribution network.
5. determine the impact of of the three techniues to reduce the power and energy losses, as well as their influence on the financial return.

References

1. J. Kennedy and R. Eberhart, “Particle swarm optimization,” in Proc. IEEE Int. Conf. Neural Networks, vol. IV, Perth, Australia, pp. 1942–1948, 1995.
2. J. Kennedy and R. C. Eberhart, “A Discrete Binary Version of the Particle Swarm Algorithm,” Proc. of the conference on Systems, Man, and Cybernetics SMC97, pp.4104-4109, 1997.
3. Y.Baghzouz and S.Ertem, “Shunt Capacitor Sizing For Radial Distribution Feeders With Distorted Substation Voltages,” IEEE Trans. Power Delivery, vol. 5, pp. 650-657, Apr. 1990.
4. J. Teng and C. Chang., "Backward/Forward sweep-based harmonic analysis method for distribution systems," IEEE Trans. on Power Delivery, vol.22, no.3, pp.1665-1672, 2007.
5. Jen-Hao Teng, “A Direct Approach for Distribution System Load Flow Solutions,” IEEE Trans. Power Delivery, vol. 18, no. 3, pp. 882–887, July. 2003.
6. H. N. Ng, M. M. A. Salama, and A.Y.Chikhani, “Capacitor allocation by approximate reasoning: fuzzy capacitor placement,” IEEE Trans. Power Delivery, vol. 15, pp. 393-398, Jan. 2000.
7. M. A. S. Masoum, A. Jafarian, M. Ladjevardi, E. F. Funchs, and W.M. Grady, “Fuzzy Approach for Optimal Placement and Sizing of Capacitor Banks in the Presence of Harmonics,” IEEE Trans. Power Delivery, vol. 19, pp. 822-829, Apr. 2004.