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Economic Evaluation of Optimal Capacitor Placement in Reconfiguration Distribution System Using Genetic Algorithm

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Abstract

Optimal capacitor placement, considering power system loss reduction, voltage profile improvement, line reactive power decrease and power factor correction, is of particular importance in power system planning and control. The distribution system operator calculates the optimal place, number and capacity of capacitors based on two major purposes: active power loss reduction and return on investment maximization. In this paper, the optimization problem of various values of economic amount of reactive power is formulated; then after evaluation of objective function and implementation of optimization algorithm for each value, the optimum capacity of capacitors and their arrangement in load nodes of power system are extracted. Also, using the proposed objective function, the threshold price of reactive power selling can be calculated; thus the investment of capacitor installation will be beneficial for distribution system operator.

Keywords: Capacitor, Optimal Placement, Economic, Genetic, Reconfiguration Distribution System

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1. Introduction

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 benefits depends greatly on how the capacitors are placed on the system. The problem of how to place capacitors on the system such that these benefits are achieved and/or maximized against the cost associated with the capacitors placement are termed the general capacitor placement problem. Optimal distribution capacitor planning is an important task for economic operation of power systems. The optimal distribution capacitor planning is a combinatorial optimization problem which considers both power losses and cost of capacitor installation subject to bus voltage constraints. Discrete nature of capacitors, different load are considered in the problem formulation. The proposed term consists of determining the locations to install capacitors and the types and sizes of capacitors in the nodes of a radial distribution system [1, 2].

An overview of methods previously considered for placement of capacitors is presented in [3]. [4] considered only peak kilowatt loss savings with fixed capacitors and ignore the cost of capacitors. In [5] savings was based on energy loss reduction considering a time-varying load, instead of considering reduction of peak power losses. [6] presented an approach for optimal placement of capacitor banks in a real power network for the purpose of economic minimization of loss and enhancement of voltage. The presented algorithm is not based on optimization procedure, but is an aid in calculating savings due to placement of capacitors. In [7] equations are given for sizing and placement of *n* capacitors on a uniform feeder with a uniformly distributed load. [8] proposed a dynamic programming approach to find the number, locations and sizes of fixed capacitor banks on a feeder with discrete loads without considering various related costs. [9] included the effect of load growth and energy cost increase into the objective function and solve the problem using the method of local variations.

Then after some different works in capacitor placement considering different technical aspects, [10] formulated the problem as a non-linear, mixed integer programming problem.

Capacitor cost is approximated by a linear function and a fixed charge. [11] modified the formulation of [10] to treat capacitor cost as a step-like function and capacitor sizes as discrete variables.

The use of genetic algorithm for placement and sizing of fixed capacitors proposed in [12-14]. After that different intelligent control methods were used for capacitor placement. [15] and [16] both proposed an Artificial Neural Network (ANN) for capacitors control. [17] proposed a solution approach to the capacitor placement problem based on fuzzy sets theory. Discrete particle swarm optimization algorithm were used for optimal capacitor placement and sizing in [18]. The main idea of [19] is to join in a single algorithm, characteristics of methodologies already established, and working together to overcome individual limitations. Optimal placement of distributed generation (DG) units and proper allocation of shunt capacitors in order to loss reduction and improvement of voltage profile in distribution systems studied in [20].

Although lots of works have been done for placement of capacitors, a minor attention has paid to its economic point of view. In this paper, this critical aspect of placement takes into consideration. Accomplishing this goal, first genetic algorithm is briefly discussed in part II. Part III, covers power flow study and problem formulation in companion with optimization algorithm. Then in part IV, the simulation results is shown. Roy- Billinton test system is considered as the testing system. Finally, the conclusion comes in part V.

2. Genetic Algorithm

Genetic Algorithms are a family of computational models inspired by evaluation. These algorithms encode a potential solution to a specific problem on a simple chromosome-like data structure and apply recombination operators to these structures so as to preserve critical information. Genetic algorithms are often viewed as function optimizers, although the range of problem to which genetic algorithms have been applied is quite broad [19].

Genetic algorithms search for an optimal solution using the principles and heredity. They operate on populations which consist of a number of individuals, each representing a particular selection of the values of the variables coded in binary form. The initial population of binary strings is randomly generated. Each individual is evaluated to obtain a measure of fitness in terms of the objective function to be optimized; then a new population is formed by selecting the fitter individuals. Some members of the new population undergo transformations by genetic operators to form new solutions. Such operators include “crossover” and “mutation”. Crossover creates new individuals by combining substrings from the parent individuals and takes place according to a given probability value. Mutation creates a new individual by changing a randomly selected bit in its coding [21].

3. Optimum Reactive Power Compensation in Restructured Distribution system

1. Power flow study

Power flow or load flow is a crucial part of power system analysis. These parameters are assumed in power flow of the system:

r_{ij}: Resistance between bus i and j;
x_{ij}: Reactance between bus i and j;
Z_{ij}: Impedance between bus i and j;
Y_{ij}: Admittance between bus i and j;
|V|: Voltage of bus i;
δ: Phase angle
P: Active power;
Q: Reactive power;

Employing KCL in this bus leads to:

$$\begin{aligned}&I_i = y_{io}v_i + y_{i1}\left(v_i - v_1\right) + y_{i2}\left(v_i - v_2\right)\\&+....y_{in}\left(v_i - v_n\right) = \left(y_{io} + y_{i1} + ... + y_{in}\right)\\&v_i - y_{i1}v_1 - y_{i2}v_2 - .... - y_{in}v_{12}I_i =\\&\sum_{j=0}^{n} y_{ij} - v_i\sum_{j=0}^{n} y_{ij}v_j \; i \neq j\end{aligned} \tag{1}$$

Active and reactive powers in this bus are [22]:

$$p_i + jQ_i = v_i I_i^* \text{ or } I_i = \frac{p_i - jQ_i}{v_i^*} \tag{2}$$

And so:

$$\frac{p_i - jQ_i}{v_i^*} = v_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} v_j, \; j \neq i \tag{3}$$

The load flow problem results in nonlinear algebraic equations which should be solved with repetitive methods.

$$I_i = \sum_{j=1}^{n} y_{ij} v_j \tag{4}$$

(4) is the same as (3) in which y_{ij} is the admittance matrix. With restating it in polar form:

$$I_i = \sum_{j=1}^{n} \left|y_{ij}\right|\left|v_j\right| < \left(\theta_{ij} + \delta_j\right) \tag{5}$$

Complex power of i^{th} bus is equal to:

$$p_i - jQ_i = v_i \times I_i \tag{6}$$

Placement of I_i results in:

$$p_i - jQ_i = \left|v_j\right| < -\delta_i \sum_{j=1}^{n} \left|y_{ij}\right|\left|v_j\right| < \left(\theta_{ij} + \delta_j\right)$$
(7)

Separating of real and imaginary part of this equation leads to:

$$p_i = \sum_{j=1}^{n} \left|y_{ij}\right|\left|v_j\right|\left|v_i\right| \cos\left(\theta_{ij} - \delta_i + \delta_j\right) \tag{8}$$

$$Q_i = -\sum_{j=1}^{n} \left|y_{ij}\right|\left|v_j\right|\left|v_i\right| \sin\left(\theta_{ij} - \delta_i + \delta_j\right) \tag{9}$$

Extension of these two equations using Taylor series and with elimination of upper degrees, linear equations are obtained [20]. In these equations, i^{th} bus is considered as the reference bus. Diametric and not diametric elements of Jacobian matrix are as below, respectively:

$$\frac{\partial p_i}{\partial \delta_i} = \sum_{j \neq i} \left|v_i\right|\left|v_j\right|\left|v_{ij}\right| \sin\left(\theta_{ij} - \delta_i - \delta_j\right) \; j \neq i \tag{10}$$

$$\frac{\partial p_i}{\partial \delta_i} = -\left|v_i\right|\left|v_j\right|\left|v_{ij}\right| \sin(\theta_{ij} + \delta_i + \delta_j)$$

$$\frac{\partial p_i}{\partial \left|v_i\right|} = 2\left|v_i\right|.\left|y_{ii}\right| \cos\theta_{ii} + \sum \left|v_j\right|.\left|y_{ij}\right| \cos(\theta_{ij} + \delta_i + \delta_j)\, j \neq i$$

$$\frac{\partial p_i}{\partial \left|v_i\right|} = \left|v_i\right|.\left|y_{ii}\right| \cos(\theta_{ij} - \delta_i + \delta_j)$$

(11)

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{j \neq i} \left|v_i\right|\left|v_j\right|\left|v_{ij}\right| \cos^1\left(\theta_{ij} - \delta_i - \delta_j\right) \; j \neq i$$

$$\frac{\partial p_i}{\partial \delta_i} = -\left|v_i\right|\left|v_j\right|\left|v_{ij}\right| \cos(\theta_{ij} - \delta_i + \delta_j)$$

$$\frac{\partial p_i}{\partial \left|v_i\right|} = -2\left|v_i\right|\left|y_{ii}\right| \sin\theta_{ii} - \sum \left|v_j\right|.\left|y_{ij}\right| \sin(\theta_{ij} - \delta_i + \delta_j)\, j \neq i$$

$$\frac{\partial p_i}{\partial \left|v_i\right|} = -\left|v_i\right|.\left|y_{ij}\right| \sin(\theta_{ij} - \delta_i + \delta_j) \ldots j \neq i$$

(12)

These points should be noted in power flow [22]:

1. For load buses, P_i^{sch} *and* Q_i^{sch} are known; their voltage and phase angle are considered 0 and 1, respectively. In voltage controlled buses, $|V_i|$ = 1 and P_i^{sch} is definite and the phase angle is equal to the reference phase angle, i.e., 0.
2. For load buses, $P_i^{(k)}$ and $Q_i^{(k)}$ is obtained using (8) and (9), $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are calculated as below:

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \tag{13}$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \tag{14}$$

The new estimation of voltages is:

$$\begin{aligned} \delta_i^{(k+1)} &= \delta_i^k + \Delta\delta_i^k \\ \left|V_i^{(k+1)}\right| &= \left|V_i^k\right| + \Delta\left|V_i^k\right| \end{aligned} \tag{15}$$

3. For voltage controlled buses, $P_i^{(k)}$ and $\Delta P_i^{(k)}$ are calculated based on (8) and (13). This procedure continues until:

$$\begin{aligned} \left|\Delta Q_i^{(k)}\right| &< \varepsilon \\ \left|\Delta P_i^{(k)}\right| &< \varepsilon \end{aligned} \tag{16}$$

The Jacobian matrix is as below:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ j & L \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\left|V\right| \end{bmatrix} \tag{17}$$

2. Problem Formulation

The comparison of present state (before compensation) and the new state (after compensation) is done in order to optimize the objective function. The economic components of present state are [23]:

1. Power loss variant price of distribution lines in power system;
2. Power loss variant price of HV/MV transformers;

After the system operation in new state and capacitor placement in load buses of medium voltage and HV/MV, the new economic components are:

3. The new amount of power loss variant price which is definitely less than the previous.
4. The new power loss variant price of HV/MV transformers;
5. The income of reactive power selling to the transmission system;
6. The total cost of capacitor installation.

All the above economic components are surveying yearly [21]. For this period, the load changes and the capacitors state are considered.

The first clause, i.e., power loss in distribution lines in h^{th} hour, considering the daily load and hourly load changes in medium voltage bus, results in:

$$P_{loss}(h)=\sum_{i=1}^{nr}\frac{R_i}{V_i^2}\left[(P_i(h))^2+(Q_i(h)-Q_{ci}(h))^2\right] \quad (18)$$

In which Q_{ci} is the installed capacitor capacity in bus i, P_i (h) and Q_i (h) are active and reactive power of *i*-th branch (including loads and losses), and n_r is the total number of network branches.

In the case of present state which no capacitor is installed, $Q_{ci}(h)=0$, and one year power loss is calculated as below:

$$E_{loss}=365\sum_{h=1.24}P_{loss}(h) \quad (19)$$

In above clauses, the third clause is similar to the first one in the case of $Q_{ci}(h)\neq 0$. The second clause related to the transformers can be extracted as:

$$P_{loss\ TR}(h)=\frac{R_{TR}}{V_2}\left[P(h)^2+Q(h)-Q_{ci}(h)^2\right] \quad (20)$$

In which R_{TR} is the series resistance of transformer, V is the nominal voltage of medium voltage network, P(h) and Q(h) are the required active and reactive power (including loads and losses) in medium voltage bus of transformer. In (20), $Q_c(h)=0$ and P_{lossTR} is the transformer loss before compensation. The losses of distribution transformers can be neglected due to their small resistances. One year transformer power loss is:

$$E_{TR}=365\sum_{h=1.24}P_{loss\ TR}(h) \quad (21)$$

The forth clause is similar to the second one in the case of $Q_c(h)\neq 0$. Indeed, this situation is related to the real operation of capacitors connected to medium voltage of HV/MV transformer in every hour of a day.

The economic profit of loss reduction in power system is obtained as below:

$$R_{ET}=(C_{ETb}-C_{ETa})=(E_{loss\,b}-E_{loss\,a})C_{ET} \quad (22)$$

In which C_{ETb} and C_{ETa} are the loss costs of before and after compensation, E_{lossb} and E_{lossa} are energy losses before and after compensation and C_{ET} is the unity energy price in Rial/kWh which is 773 Rial/KWh based on Iran Budget Law in 2011.

The profit of loss reduction in HV/MV transformer is:

$$R_{ETR}=(C_{ETRb}-C_{ETRa})=(E_{TR\,b}-E_{TR\,a})C_{ET} \quad (23)$$

C_{ETRb} and C_{ETRa} are the transformer loss costs of before and after compensation and E_{TRb} and E_{TRa} are the energy losses before and after compensating.

If R_{ET} and R_{ETR} are less than zero, it means that not only no profit is achieved but also economic lose is occurred for distribution operator, i.e., the capacitor installation cost is more than the loss reduction cost.

For stating (22) that is the income of reactive power selling to the transmission system, R is considered for Rial value of one kilo Volt Ampere Reactive (VAR) in Rial/KVARh and R_T for Rial value of total reactive power of installed capacitors; thus [23]:

$$R_T=365R\sum_{i=1}^{n}\sum_{h=1}^{24}Q_{ci}(h) \quad (24)$$

In which n is the total number of network buses and $Q_{ci}(h)$ is the amount of reactive power of capacitors in i^{th} bus and h^{th} hour. The main problem is optimum determination of R using Genetic algorithm.

Finally, the sixth clause is the whole cost of purchasing, installation and maintenance of capacitors that is [8]:

$$C_{instT}=C_{inst}\times Q_{cint} \quad (25)$$

$C_{inst}$is the cost of one KVAR producing by capacitors and Q_{cinst} is their installed capacities.

For answer evaluation, an index should be defined which is return on investment (ROI) index in this paper.

3. Optimization Algorithm

The aim of an optimization algorithm manipulation is maximizing the objective function. The proper capacitance and place of installing capacitors will be searched using this optimization algorithm and the load flow program.

3.1. Solving the problem of capacitor installation in restructured distribution system with Genetic algorithm

The solving procedure is as below:

3.1.1. The system data is entered and the load flow is done, then all the load buses are considered as the candidate bus to install capacitor. An initial capacity is defined in order to start searching based on objective function and Genetic algorithm utilization. The input data of this program is: active and reactive load power in network buses, impedance and admittance of lines, the maximum permissive number of capacitors in each bus, the price of one kWh energy in Rial, the cost of purchasing and installing of one KVAR of capacitor and the price of its selling to the transmission network. The decision variables include: the place and capacity of installed capacitors and their control variables including their maximum capacity, permitted range of bus voltage and the maximum permissive amount of sold reactive power which is not causing unstable generator. The output data also includes: the final place and capacity of capacitors in network, active and reactive power losses after compensation, HV/MV transformer power losses and the amount of sold energy to the transmission system.

*3.1.2.*An objective function manipulation for capacity determination; this paper uses the ROI index. This index is a proper index because the goal is maximizing the economic profit and Genetic algorithm is optimizing the objective function.

$$\max\text{imize}\ \{\text{ROI}\}:\left\{\frac{\mathrm{R_{ET}}+\mathrm{R_{ETR}}+\mathrm{R_{T}}-\mathrm{C_{inst\ T}}}{\mathrm{C_{inst\ T}}}\right\} \quad (26)$$

The constraints of this objective function are:

$$\begin{aligned} &V_{i\min} < v_i < V_{i\max}\ , \\ &Q_{c(\min)} \le Q_c \le Q_{c(\max)} \quad 0 \le n_i \le n_{i(\max)} \end{aligned} \quad (27)$$

In which n_{i} is the number of capacitors in i^{th} bus. In (26), if the numerator is more than zero, the net income increases with the installed capacity growth. The threshold price is the specific price in which the ROI index changes from a negative value or zero to a positive one. In order to compute the capacitors final place and capacity for each value of *R*, the program should be repeated until the maximum number of permitted repetition was done or the total practice chromosomes in one generation reached a constant value. However, generally, due to the gene mutation, a constant value for total practice chromosomes cannot be achieved and it oscillates around a constant value. In this case, the obtained answer is saturated and that is the optimum answer of Genetic algorithm; then *R* is increased one step and the algorithm repeats.

The configuration and capacitance of capacitors based on algorithm manipulation for every *R* value leads to the maximum income for distribution operator. For the case of *R*=0, the profit of reactive power selling is eliminated; thus the goal is searching for the optimal configuration and capacitance of capacitors without energy selling and restructuring power system consideration.

3.2. Problem solving algorithm

As it is shown in fig. 1 and mentioned before, the problem solving process can be summarized as below:

1. Initial population formation (initial capacitance determination as the candidate chromosomes in initial population)
2. Best value evaluation for each chromosome and objective function assessment; load flow based on initial capacitor population for each chromosome; power loss calculation of lines and transformers for this configuration; computation of capacitor installation cost for this configuration; R_{T} calculation for various *R* values; fitness function calculation for each chromosome (objective function value); best value determination of each population for reproduction
3. Reproduction using compound operators and genius mutation
4. Second and third step repetition until the maximum determined reproduction is achieved or the fitness function is saturated
5. Capacitance determination for each candidate considering the best produced chromosome

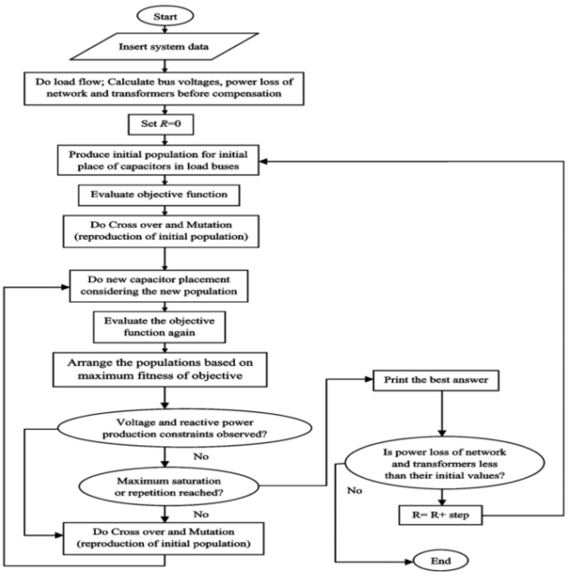

Fig.1. Capacitor placement algorithm in restructured distribution system using Genetic method

4. Simulation Results

The proposed method is simulated and tested on an IEEE radial system. An m-file program is written based on Genetic algorithm and Newton- Raphson load flow for various loading cases in a distribution system.

4.1) Problem formulation in MATLAB

The test system simulation is done employing two matrices: input matrix of bus data and matrix of line data.

4.1.1. Input matrix of bus data

Column 1: bus number
Column 2: bus code (PQ bus: 0, reference bus: 1, PV bus: 2)
Column 3: voltage magnitude in p.u.
Column 4: phase angle in degree
Column 5: bus load in MW
Column 6: bus load in MVAR

Columns 7 to 10: generated MW, generated MVAR, minimum permitted MVAR
Column 11: injected reactive power (MVAR) by parallel capacitors

4.1.2. Matrix of line data

In this matrix, each line is specified by two buses. The first and second columns are the starting and ending buses number of lines, respectively. Columns 3 to 5 are resistance, reactance and half of the susceptance of the whole line in p.u. and with determined bases. The capacitance susceptance is neglected due to its negligibility in distribution systems. The last column is applying for regulation of transformers tap-changers; it should be 1 for lines. The lines data can be entered in any order except the transformers in which the tapping side is considered as the left bus. The load flow program and genetic algorithm should be connected after entering the system and lines data. The genetic program output should be considered as the 11th column input of bus data matrix; thus the load buses is contemplated as the initial population of genetic algorithm and a suitable initial capacity should be considered for them. Due to discrete capacities of available capacitors, the bites of chromosomes are valued as equal as the real steps of capacitors. In this program, the ROI index is applied as the fitness of objective function.

4.2. Roy- Billinton Test System Simulation (RBTS)

4.2.1. Program implementation assuming an average load for all hours of a year

Roy- Billinton test system has 71 buses and 38 load buses. The capacity steps of installed capacitors in load buses of such a system are 150 KVAR. The system diagram is illustrated in fig. 2. The maximum number of installed capacitors in each bus is 8 (maximum of 1200 KVAR) and the maximum number of installable 1200kVAR capacitors in 230/33 kV station is 28 (maximum of 33.6 MVAR). The transformer of 230/33kv station is 160 MVA and has a series resistance of 0.024 ohm. The system loss before capacitor installation is 739 kW. The average active and reactive loads connected to the system are 24.578 MW and 15.232 MVAR, respectively.

Through program running- considering average load for all hours of a year- for each R value (the Rial equivalence of each kVARh) and with optimum answer detecting based on genetic algorithm, the final power loss of system, transformer power loss in 230/33kV station, the total installed capacity, fitness of objective function (ROI index), required reactive power of system (including loads reactive power and reactive power losses) and received/sent reactive power from/to the transmission system is extracted as shown in Table.1.

As it mentioned before in table I, Q_{cinst} is the total installed capacity in system, $Q_{\text{load+loss}}$ is the total reactive power of loads and system and $Q_{\text{surplus}}$is the surplus installed capacity for selling the transmission system.

Table.1
The program results with changing R and considering average load

R (Rial/kvarh)	P_{loss} (kw)	P_{lossTR} (kw)	Q_{cinst} (kvar)	Q (load+loss)	Q_{surplus} (kvar)	ROI
0	494.800	19.271	11850	15712	-3862	-0.73941
5	486	19.274	13500	15699	-2199	-0.67232
10	482.440	19.320	13500	15694	-2194	-0.58243
15	482.150	19.319	14850	15689	-839	-0.5395
20	486.02	19.326	15150	15690	-540	-0.45239
25	484.890	19.325	15150	15689	-539	-0.37253
30	484.180	19.324	15600	15688	-88	-0.27258
35	486.470	19.326	15600	15687	-87	-0.19973
40	485.770	19.325	15600	15670	-70	-0.13192
45	489.440	19.330	17400	15688	1712	0.031983
50	489.650	19.360	20850	15698	5152	0.059901
55	508.890	19.360	23700	15696	8004	0.16491
60	518.370	19.381	28350	15729	12621	0.2073
65	557.790	19.445	32400	15712	16688	0.29786
70	620.680	19557	35700	15778	19922	0.3942

It should be noted that for R values close to zero, the installed capacity has a low variation and as expected the ROI index is negative. Indeed, the surplus reactive power is negative before the threshold price or the distribution system receives reactive power from transmission system which is the worst case because while it is not profitable for distribution operator, it does not produce required reactive power. As the ROI index gets positive, the threshold value of R is approximately 45 Rials. In fact, if the distribution operator sells each kVAR reactive power to the transmission system with the price of 45 to 70 Rials, it can increase the installed capacity from 17400 to 35700 kVAR which is installed in 230/33kV station mostly. On the other hand, raising the price over 70 Rials increases the distribution system income, however the system power loss increases comparing to before compensation; also the maximum permitted injecting MVAR constraint is reversed. Considering the first goal of capacitance installation which is power loss reduction, the distribution operator is not permitted to such a price increase. The table of final configuration and optimal capacity of installed capacitors in each bus with various values of R is presented in appendix 3. The diagram of system power loss, transformer loss in HV/MV, total installed capacity and the ROI index for various values of R is illustrated in fig.2 to fig.5.

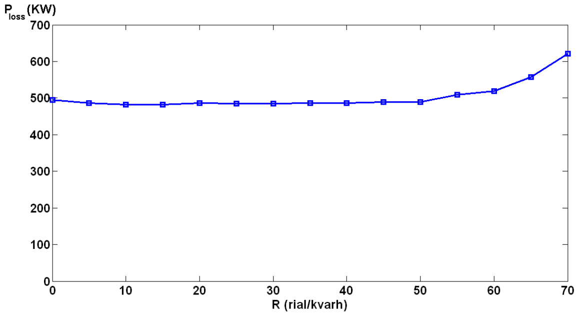

Fig.2. System power loss for various values of R

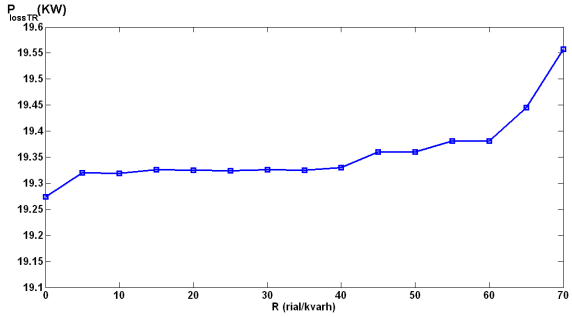

Fig.3. 230/33 transformer loss for various values of R

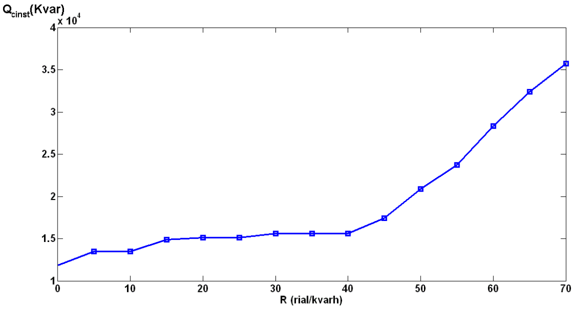

Fig.4. Installed capacity in system for various values of R

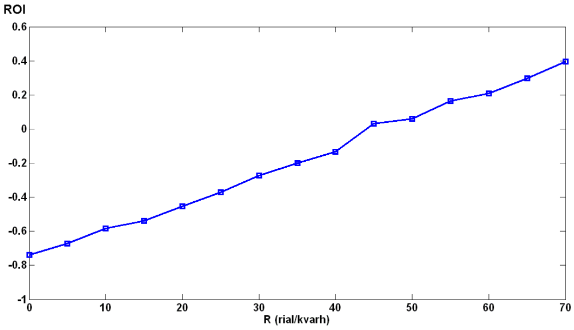

Fig.5. ROI index for various values of R

As mentioned before, in the threshold price the ROI index changes from a negative value or zero to a positive value. In fig.5, 45 Rials is the threshold price. Studying the calculated capacities of each bus, it can be deduced that with R increasing from its threshold value, the installed capacitors have mostly similar configuration and for economic benefit enhancement, the 230/33kV station capacitor should be changed. The reason is that in HV/MV station (joint station of distribution and transmission), there are a lot of feeders with reactive load and as a result the maximum permitted number of installing capacitors in this station is more than the load buses.

4.2.1. Program implementation assuming variable daily load for all hours of a year

In this part, the proposed method is tested on the same system, i.e., Roy-Billinton, and assumed that the load is changing during 24 hours a day (fig.6). Finally the results are studied.

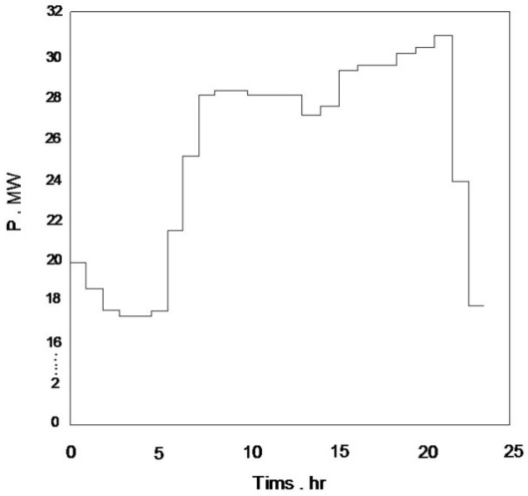

Fig.6. 24-hours load diagram of four bus of Roy-Billinton

With program running for the test system and with the shown load diagram, for each R value and repetitive employment of genetic algorithm, the final answer of power loss in system, power loss in 230/33kV transformer in a year, the total installed capacity and the ROI index are extracted as Table.2.

Table.2
The program results with changing the 24-hours load

R(Rial/kvarh)	P_{loss} (kw)	$P_{loss\ TR}$(kw)	Q_{sinst}(kvar)	ROI
0	2926.38	-1	13800	99.39
5	2936.73	-0.80974	14550	99.45
15	2972.54	-0.63655	14550	99.5
25	2869.35	-0.46279	18900	99.52
35	3247.47	-0.32181	21150	100.36
45	3241.71	-0.14872	21150	100.65
55	3557.13	0.00299	24900	100.93
60	3728.24	0.055728	27000	100.99
65	3769.54	0.16087	27600	101.23
70	3993.1	0.2555	27750	101.44
75	4006.69	0.32981	30900	102.76
80	4232.14	0.44149	31650	104.95

As it can be seen, for the values of R which are close to zero, the installed capacity is mostly constant again and the ROI index is negative. With R rising, the mentioned index increases gradually in companion with the installed capacity. This increasing is slow until reaching the threshold price and then increases faster as soon as gets the threshold price. This procedure is the same as expected: surplus capacitor installation comparing the system required capacity is economically beneficial if the distribution operator buys the reactive power with a proper price. In this case and with daily load changing, the threshold value of R is obtained 55 Rial. In fact, in selling each kVARh of reactive power with the price of 55 Rials or more to the transmission system, the investment in capacitor installation is mostly economically beneficial to the distribution operator in comparison with power loss reduction. The diagram of lines and main station transformer power loss, installed capacity and ROI index for various values of R which are shown in fig. 7 to 10 proves this fact.

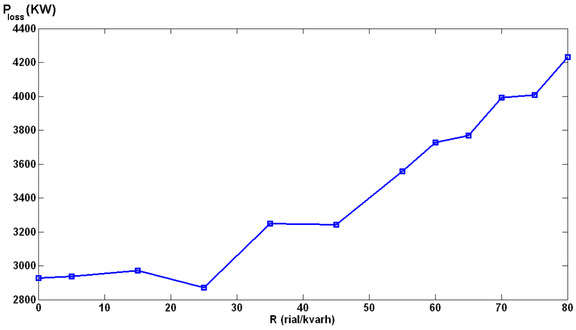

Fig.7. System power loss for various values of R in a year

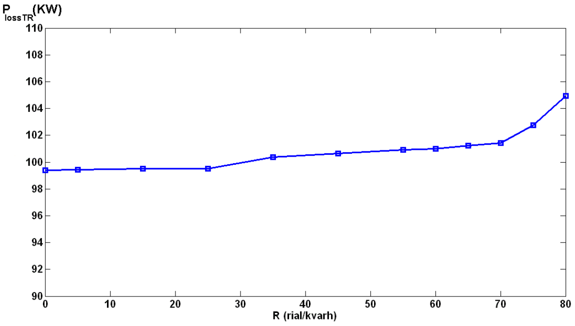

Fig.8. 230/33 transformer loss for various values of R in a year

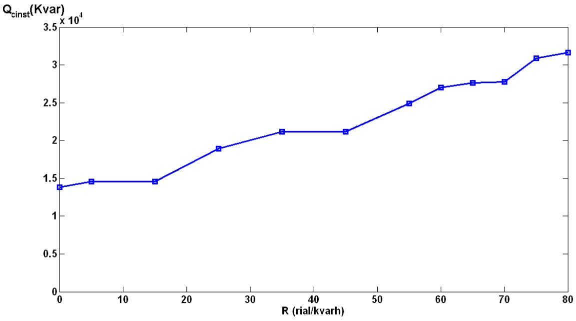

Fig.9. Installed capacity in system for various values of R

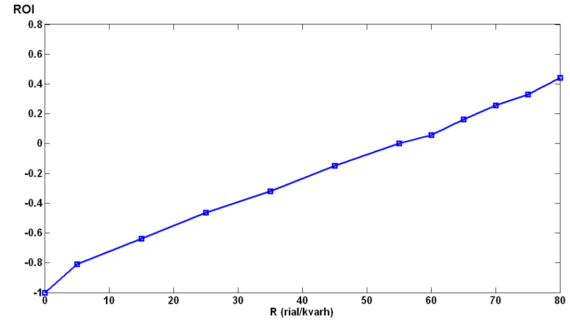

Fig.10. ROI index for various values of R

It should be noted that with using the proposed program, the installed capacity in load buses in each hour of the day will be determined. Based on the obtained capacities, the hourly switching situation of capacitors is concluded.

In Fig. 11 the switching state in the case of R=0 is presented. Similarly, the switching state in other prices is determined in the program; however the annual exchanged energy is presented in terms of R because of the large mass of data. In Fig. 12 the exchanged reactive power in a year is illustrated considering each R parameter.

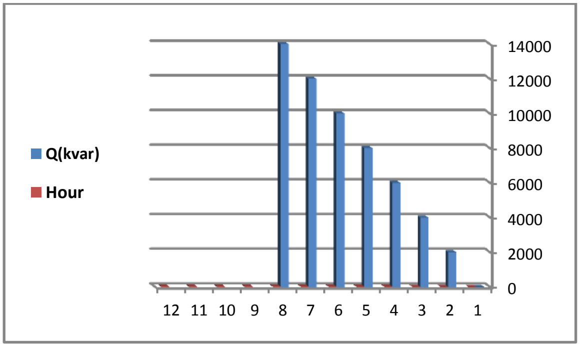

Fig.11. Daily installed capacity change in R=0

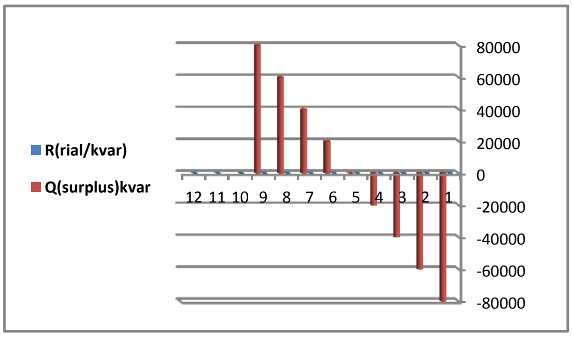

Fig. 12. Purchased/ sold reactive power in a year

Obviously the devoted economic value to the sold reactive power (R) should be logical. This economic value for the distribution operator cannot be less than a determined threshold value.

If the transmission system obtains the reactive power with a higher value than the threshold, the capacitor installation and operation is profitable, and if it is lower, there is no need for compensation exceeding the power loss reduction necessity. This occurs when the reactive power production and transmission is cheaper than buying from the distribution system.

For the R values which are less than the threshold value, the installed capacity and system power loss are almost constant and the parameter changes lead to the similar configurations of capacitors in load buses of the power system. In this case, the produced reactive power in the distribution system is equal to or less than the loads reactive power and the reactive losses; thus, it probably receives its reactive power from the transmission system partially or overall, considering the reactive unit price and purchase cost, capacitors installation and maintenance. With the increasing of R value and reaching the threshold margin, the installed capacitance increases with the enhancement of ROI.

5. Conclusion

With our problem formulation of placement and optimal capacitance of capacitors in a restructured distribution system, using Roy- Billinton test system as our case study, these results is achieved:

- Before restructuring, a distribution system supposed to improve the voltage profile and reduce the system loss which is possible through reactive power compensator installation.

In restructured distribution systems, the amount of installed capacitance for power loss reduction depends on the market situation. In our new method, investment in compensation installation has two advantages for distribution operator: power loss reduction and profit enhancement of reactive power selling. The power system and transformer loss increases to some extent simultaneously with the economic profit enhancement of investing in capacitance installation more than system requirement. The reason is that the reactive power increasing in load power buses is more than their demands which leads to power loss increasing. If the reactive power price calculates without noting the constraints, the obtained economic profit leads to power loss increasing; thus, the price increment more than the threshold value is also limited.

- A great amount of sold reactive power to the transmission line is installed in HV/MV station because of limitations in permitted number of capacitance banks in load buses, maximum injecting M VAR and voltage range in each bus. Consequently, it can be deduced that the installed capacitance in MV buses are used for power loss reduction and the HV/MV stations capacitors are utilizing for investment and energy selling to the transmission operator.

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