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## HSA-Based Optimal Allocation and Sizing of Shunt Compensators Considering Cable Aging Constraint and Load Variations

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**Abstract.** Aging of power system equipments can be caused by erosion of metallic structures such as cable sheathing. Higher system risk due to higher failure probability and possible system damage following the end-of-life failure, are the direct consequence of cable aging. One of the solutions to solve this problem is the reduction of the cables current flow using different solutions in the power system network. In this paper, an HSA-Based optimal placement and sizing of shunt compensators is proposed to reduce the current flow. The IEEE RTS 24-Bus network is selected to verify the proposed algorithm with and without considering load variations during a year. The obtained results show the possibility of slowing of the cable aging in the studied network using shunt compensators.

### Keywords

Cable aging, Shunt compensator, HSA, Load variations, IEEE RTS 24-Bus.

## 1. Introduction

There may be different causes of aging for different kinds of equipment. Aging can be caused by erosion of metal structures (such as underground cable sheathing), fatigue damage of mechanical parts (such as generators and motors), or insulation deterioration of electrical components (such as transformers and reactors). Like human beings, any equipment will experience its wear-out stages, normal operation, and infancy. As a piece of

equipment ages, it fails more frequently, eventually reaches its end of life, and needs longer time to repair. Higher system risk due to higher failure probability and possible damage of system following the end-of-life failure is the consequence of cable aging. Utilities normally carry out regular inspections and preventative overhauls. The maintenance activities can extend the life of equipments but could be costly for equipments at their end-of-life stage. Therefore, a compromise between replacement and maintenance must be carefully considered.

Recently many studies have been conducted on cable aging in networks [1-6]. In [5], the effect of the cable aging has been considered in optimal allocation and sizing of DGs in power system. In this paper, Harmony Search Algorithm (HSA) is used to find the optimal allocation and sizing of shunt compensators in order to solve the cable aging in the power system network. The effectiveness of the proposed algorithm is demonstrated through IEEE RTS 24-Bus standard test network simulations with and without considering the load variations during a year.

## 2. Cable Aging Process and Maintenance

The probability of end-of-life failures increases with cable aging and aging process can be slowed through the maintenance activities. There are two kinds of maintenance: corrective and preventative. The corrective maintenance is a repairing activity after a cable failure and deals with a repairable failure. The preventative maintenance is an inspection or overhaul activity before a failure. The major goal of the preventative maintenance is to reduce deterioration and prolong the lifetime of the

cable, and it addresses both end of life and repairable failures. The economic or usable value of the cable is reduced as it ages, and preventative maintenance activities can delay the aging process. The relationship between the preventative maintenance, time, and value is shown in Figure 1. It can be seen that maintenance can recover a part of the lost value caused by the deterioration in the aging process. However, although maintenance can slow the aging, it cannot fully stop it.

There are two methods for implementing preventative maintenance: predictive and regular. The predictive maintenance has been implemented in some utilities in the past 10–15 years and addressed in the power industry. This method needs an assessment process including calculations and mathematical modeling, condition monitoring, and appropriate criteria. The regular maintenance is planned for fixed intervals while the predictive maintenance is undertaken as needed. The regular maintenance is based on the experience of the maintenance personnel or manufacturer's specification and is the course most widely used by utility. This method is easy and simple to perform but may result in either higher costs (doing unnecessary maintenance activities) or high system risk (not doing in time necessary maintenance activities).

As shown in Fig. 1, if the ratio of the current flow to the nominal current in each branch reduces, the cable life will be prolonged. In this paper, the cable aging is modeled in the objective function. In other words, the following equation should be minimized:

$$C_1 \sum_{i=1}^{N_{branch}} \frac{\text{Nominal life of cable } i}{\text{Prolonged life of cable } i \text{ after compensation}} \quad (1)$$

In this paper, it is assumed that the compensator is a shunt device. The costs of the reactive power injection should be considered in the objective function. Therefore, the objective function should be defined as follows:

$$C_1 \sum_{i=1}^{N_{branch}} \frac{\text{Nominal life of cable } i}{\text{Prolonged life of cable } i \text{ after compensation}} + C_2 \sum_{i=1}^{N_{bus}} Q_{compensator}^{pu} \quad (2)$$

where,  $C_1$  and  $C_2$  are weighting factors and  $Q_{compensator}^{pu}$  is the cost of the reactive power injection. In this paper, we have  $C_1/C_2 = 0.5$ , because the minimization of the injected reactive power, i.e.  $Q_{compensator}^{pu}$ , is more important. The relationships between voltage profile and network loss have been studied in [7] considering compensators sizing and placement. The goal of this paper is considering the cable aging in this issue. Therefore, in order to focus on cable aging, it is assumed that the effects of network loss and voltage profile are neglected through the cost function calculation. In the next section, an optimization algorithm will be described and used for finding the optimal number, injected reactive power values and location of shunt devices.

### 3. Harmony Search Algorithm

HSA has been extracted and developed from the music improvisation process, in which music players improvise their instrument pitches to get better harmony [8-14]. The procedure of HSA is described in the next five steps:

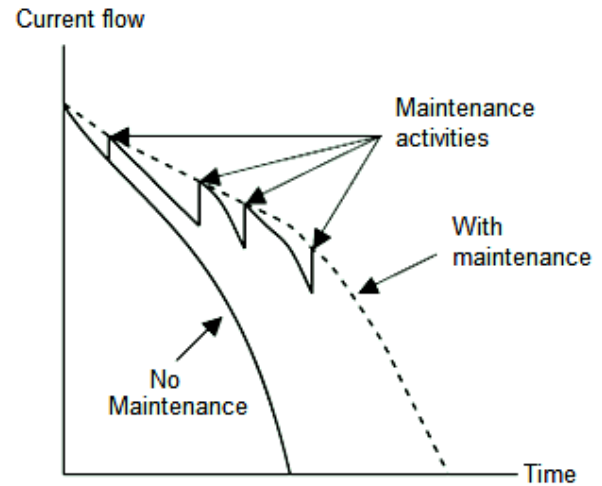


Fig. 1. Relationship among time, preventative maintenance, and current value

*Step 1: Initialize the algorithm parameters and problem*

The optimization of the problem is specified as follows:

$$\min\{f(x) | x \in X\} \quad (3)$$

$$\text{subject to: } g(x) \geq 0 \text{ and } h(x) = 0$$

where the inequality constraint function is  $g(x)$ , the objective function is  $f(x)$ , and the equality constraint function is  $h(x)$ . The set of each decision variable is  $x$ , and the set of the possible range of values for each decision variable is  $X$ , that is  $X_{i,min} \leq x_i \leq X_{i,max}$ , where,  $X_{i,max}$  and  $X_{i,min}$  are the upper and lower bounds for each decision variable, respectively. In the first step, the HSA parameters are also specified. These are the number of solution vectors in the harmony memory ( $HM$ ), or the harmony memory size ( $HMS$ ), number of decision variables ( $N$ ), harmony memory considering rate ( $HMCR$ ); pitch adjusting rate ( $PAR$ ) and the number of improvisations ( $NI$ ), or stopping criterion. Similar to the genetic pool in GA the  $HM$  is a matrix, where all of the solution vectors are stored in it [11]. Here,  $PAR$  and  $HMCR$  are parameters that both of them are defined in Step3 and used to improve the solution vector.

*Step 2: Initialize the harmony memory*

The  $HM$  matrix will be filled with as many randomly generated vectors as the  $HMS$ , in Step 2, as follows:

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \dots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \dots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \dots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \dots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \quad (4)$$

*Step 3: Improvise a new harmony*

The new harmony vector is generated based on three rules: random solution generation, pitch adjustment and memory consideration. Creating a new harmony is called 'improvisation' [10]. The value of the first decision variable  $x_1$  for the new vector in the harmony memory consideration is chosen from any value in the specified range of  $HM$  ( $x_1^1$  to  $x_1^{HMS}$ ). In the same approach, values of other decision variables ( $x_2, \dots, x_N$ ) are chosen. ( $1-HMCR$ ), which varies between 0 and 1, is the selection rate of one

value from the possible range of values randomly, while *HMCR* is the rate of choosing one value from the historical values stored in the *HM* as follows:

$$\left. \begin{array}{l} x_i' \in \{x_i^1, x_i^2, \dots, x_i^{HMS}\} \text{ with probability } HMCR \\ x_i' \in X_i \text{ with probability } (1-HMCR) \end{array} \right\} \rightarrow x_i' \quad (5)$$

For example, an *HMCR* of 0.60 indicates that the decision variable will be chosen from historically stored variables in the *HM* with the 60% probability or from the entire possible range with the 40% probability. The elements that get by the memory consideration is examined to determine whether or not it should be pitch-adjusted. This operation uses the *PAR* parameter, which has the rate of pitch adjustment, as follows:

$$\left. \begin{array}{l} Yes \text{ with probability } PAR \\ No \text{ with probability } (1-PAR) \end{array} \right\} \rightarrow \text{pitch adjusting decision for } x_i' \quad (6)$$

The rate of doing nothing with the decision variable value is set by the value of  $(1 - PAR)$ . If the pitch adjustment decision for  $x_i'$  is Yes,  $x_i'$  is replaced as follows:

$$x_i' \leftarrow x_i' \pm rand() * b_w \quad (7)$$

where,  $b_w$  is the distance bandwidth that in step 1 is set and  $rand()$  is a number that randomly varies between 0 and 1.

In Step 3, the random selection or pitch adjustment and *HM* consideration is applied to each variable of the New Harmony Vector (*NHV*) in turn.

#### Step 4: Update harmony memory

If the *NHV* is better than the worst harmony in the *HM*, the new harmony vector is included in the *HM* and the existing worst harmony is excluded.

#### Step 5: Check stopping criterion

If the maximum number of improvisations is reached, the computation is terminated. Otherwise, Steps 3 and 4 are repeated.

## 4. Simulation Results

The IEEE RTS 24-bus test system, used in this paper, is shown in Fig. 2. The objective function is defined in equation 2 such that  $0.95 \text{ p.u.} \leq V_i \leq 1.05 \text{ p.u.}$  ( $1 \leq i \leq 24$ ),  $N_{branch} = 38$  and  $N_{bus} = 24$ . Every row of the *HM* matrix has 48 elements, the first 24 elements of rows indicate the busses that the shunt compensator should be installed there, and the second 24 elements show the reactive power that should be injected by the compensator. Table 1 shows a row of the *HM* matrix.

Table I. Each row of *HM* matrix

compensator at bus 1 (0 or 1)	compensator at bus 2 (0 or 1)	...	compensator at bus 24 (0 or 1)	$Q_{injecte}^1$	$Q_{injecte}^2$	...	$Q_{injecte}^{24}$
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It should be noted that the first 24 elements are 0 or 1 and other elements are selected between 0.05 pu and 0.25 pu. In each iteration, HSA finds a better solution that leads to a less value of objective function.

These values are saved in the *HM* matrix. This network is simulated with and without considering variations in the loads during a year. Without considering the load variations, the value of the objective function is shown in Fig. 3 for 100000 iterations. Figs. 3 and 4 show the minimum and mean values of objective function versus the number of iterations, respectively. These two figures show the acceptable convergence and performance of the HSA for this problem.

According to the final results of HSA, the shunt compensators should be placed at buses 8 and 22. The setting of the injected reactive power at buses 8 and 22 are set to 0.2274 pu and 0.2116 pu, respectively.

In order to considering the load variations, the reactive and active power of the load at one bus (bus 18 in this simulation) varies with a Gaussian distribution through Monte Carlo simulation [15]. For each vector of *HM* matrix, the objective function is calculated and the mean of load variations is shown as the results. The output of the objective function considering load variations is shown in Fig. 5 for 10000 iterations. Figs. 5 and 6 show the minimum and mean values of objective function versus the number of iterations, respectively. These two figures show the acceptable convergence and performance of the HSA for this case, as well.

According to the final results of HSA in this case, the compensators should be placed at buses 7,8,11 and 23. The setting of the injected reactive power at buses 7,8,11 and 23 are set to 0.2326 pu, 0.1845 pu, 0.0836 pu and 0.2343 pu, respectively. It is obvious that the optimization procedure results in better solution (lower value of the objective function), if the load variation does not considered. But considering the load variation has more real results.

## 5. Conclusion

In this paper, the optimal allocation and sizing of shunt compensators has been proposed based on HSA to reduce the cable aging. As shown in the results, the IEEE RTS 24-bus system with and without load variations, has been used to show the importance of this study. The values of the injected reactive power and busses for the installation of compensators have been determined in order to slow the cable aging.

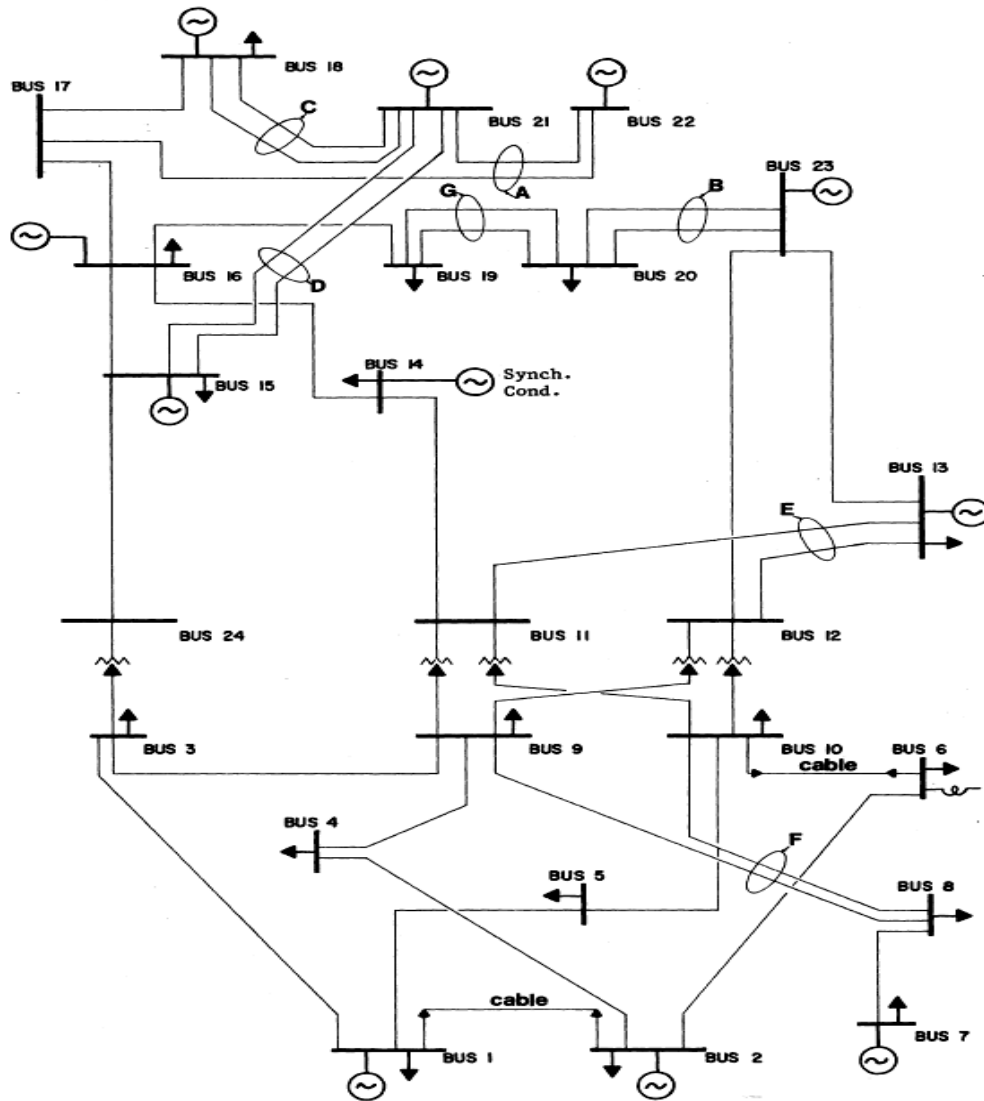


Fig. 2. IEEE RTS 24-bus test system

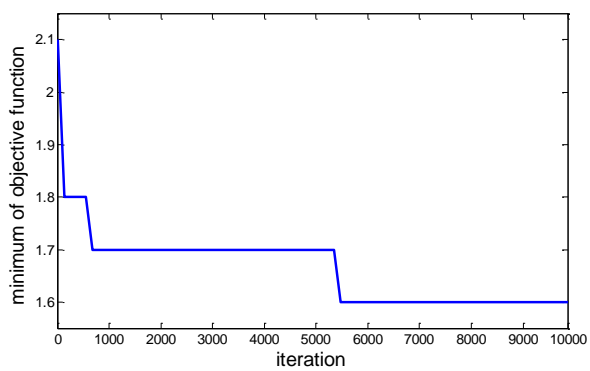


Fig. 3. Minimum value of  $HM$  matrix versus number of iterations (without considering the load variation)

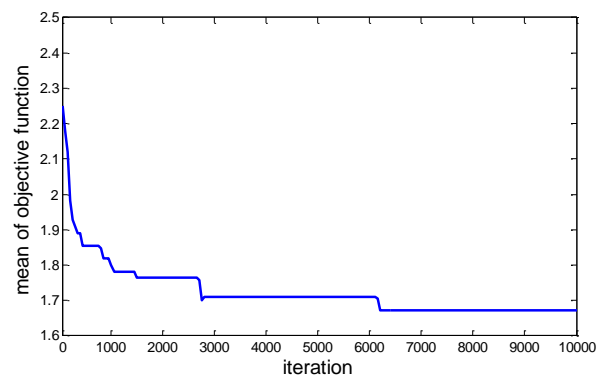


Fig. 4. Mean value of  $HM$  matrix versus number of iterations (without considering the load variation)

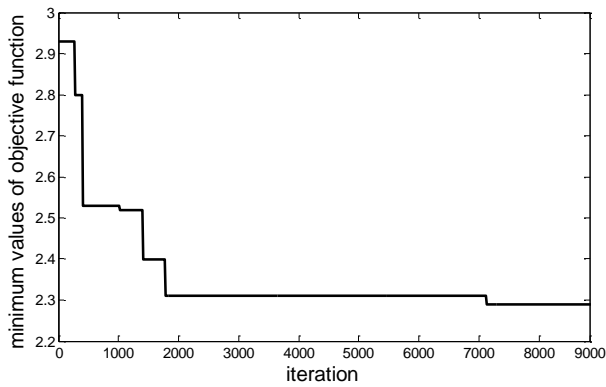


Fig. 5. Minimum value of  $HM$  matrix versus number of iterations (with considering the load variation)

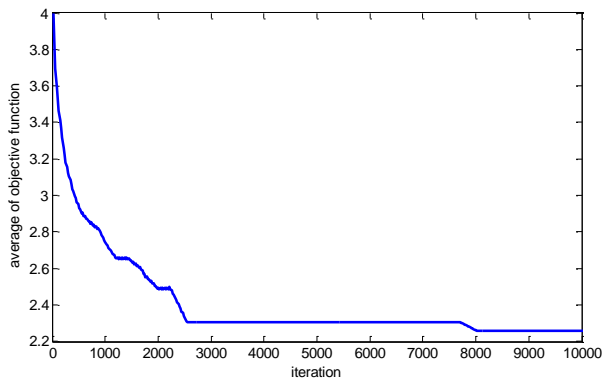


Fig. 6. Mean value of  $HM$  matrix versus number of iterations (with considering the load variation)

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