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INCORPORATING SVC PLANNING TO RECONFIGURATION BASED ON VOLTAGE SECURITY MARGIN

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Abstract- The problem of optimum reconfiguration with FACTS devices planning in distribution systems is a task that must be solved in an optimal manner for distribution companies. Also, FACTS devices such as Static VAR Compensator also have been planned for loss reduction and voltage profile improvement in steady state conditions. This problem has been modeled as a non-linear and multi objective optimization problem based on a multi-stage hieratical optimization problem to improve power system voltage stability margin and reduce losses. This reconfiguration algorithm starts with a radial topology by a theoretical approach based on the Graph concept and Matroid theory. The presented approach is useful to avoid tedious mesh checks for the topology constraint validation. Also, the voltage stability index is calculated to evaluate static voltage stability security margin. This calculation is done for each configuration pattern with defined SVCs planning. A toolbox has been developed to recognize loadability limit.

Keywords: Reconfiguration, Voltage Stability (VS), Graph and Matroid Theory, Loadability Limit, Static VAR Compensator (SVCs).

I. INTRODUCTION

Also, the trend of the de-regulated power system operation is also causing over loading of some of the distribution system buses. The application of FACTS devices to enhance the power transmission also involves reactive power control/voltage stability problems.

In a day-to-day operation of power system, preventing 'loss of voltage control', instability requires sitting additional capacitors or SVCs to maintain reactive reserves on generators, SVCs or synchronous condensers that otherwise exhaust reactive reserves and lose voltage control. Static VAR compensators are used by utilities in both Voltage and closely associates with power delivering capability. The voltage instability phenomena, which can occur in distribution systems, may not be new to power system practicing engineers and researchers. The decline of voltage stability level is one of important factors which restrict the increase of load served by distribution companies.

Hence, it is necessary to consider voltage stability constraints for planning and operation of DS with SVCs size selection and placement of SVCs. Also, the topological structure of the radial distribution systems besides of SVCs allocations is reconfigured for improving the operating conditions from time to time. Regarding to these matter, reconfiguration, SVCs placements and SVCs size selection (SVCs planning) are increasingly drawing great attention of engineers. Therefore, mixing of reconfiguration and SVC planning to improve voltage stability margin, minimize the deviation of the bus voltage, minimizing installation cost of SVC, and decreasing power losses of DSs is mentioned in this paper.

Also, there are many technical benefits of employing reconfiguration in existing DS, such as improvement line losses, economic, reliability indicators, voltage control issue, load balancing which investigated in previous literatures. The reconfiguration of distribution systems is usually done to minimize real power losses.

Until yet, many studies have been done on reconfiguration scenarios to reach the optimum conditions in distribution systems. In this field, GCPSO and graph theory is used to improvement voltage profile and loss [1]. Also, using Genetic Algorithm based on the Matroid theory is suggested in [2]. Many reconfiguration methods based on heuristics optimization, artificial intelligence methods and evolution programming can be found in the literature too. Sensitivity and heuristics method based on loss minimization is used by Viswanasha et al [3]. Saffer et al presented a new combined method for optimal reconfiguration using a multi-objective function with fuzzy variable [4]. This method considered both load balancing and loss reduction in the feeders as objective function.

The authors in [5] used DSTATCOM allocation to mitigate losses and improve voltage profile via reconfiguration in DS. Furthermore, DS reconfiguration has a potential to improve the system voltage stability too. M.A. Kashem et al [6] presented the relationship between voltage stability and loss minimization. It can be shown that voltage stability is maximized when power losses are minimized in the networks. In [7], a new method for optimal reconfiguration was suggested for radial distribution systems. Then, the several performance criteria considered for optimal network reconfiguration, which maximizing loadability is an important one. Owing to the discrete nature of the solution space, a fuzzy adaptation of the evolutionary programming algorithm for optimal reconfiguration of radial distribution systems to maximize loadability is proposed in this reference.

In [8], the authors reported a reconfiguration algorithm based on Tabu search for maximizing the security margin to voltage collapse. M. Arun et al [9] presented a new reconfiguration algorithm that enhances voltage stability and improves the voltage profile besides minimizing losses. A fuzzy genetic algorithm was reported by N.C. Sahoo et al. This algorithm is used for reconfiguration of radial distribution systems to improve the voltage stability security margin for a specific set of loads [10].

J. Olamaei et al [11] presented a new approach to distribution system reconfiguration at the distribution networks considering DGs. The main objective of this paper is to minimize the deviation of the bus voltage, the number of switching operations and the total cost of the active power generated by DGs. Ant colony algorithm is used to aim the minimum power loss and increment load balance factor of radial distribution networks with DGs [12]. In [13], a tabu search algorithm is applied to search for the on/off patterns of the sectionalizing switches and tie switches to obtain the minimum total power loss, whereas the dispatch schedule of the distributed generators which gives the minimum total cost of generation is solved by an optimal power flow.

Presence of compensation units like SVC with regards to their effects on system operation point, can trace on optimal configuration. Since feeder reconfiguration and reactive power control are two important means of reducing power losses and improvement voltage stability margin of DSs, the idea of coordinated application of these two controls has been investigated.

Static VAR compensators are used by utilities in both transmission and distribution systems. The primary purpose is usually rapid control of voltage at weak points in a network. There are two major applications of installation of static VAR compensators in a power system. One of the main reasons is related to load compensation and the other is to avoid voltage fluctuations [14].

There are two main reasons for compensating fluctuating loads:

- The AC system is too weak to maintain the terminal voltage within the acceptable variations.
- It is neither economical, nor practical to supply the reactive power demand from the AC system.

Installation of SVC at these load buses help in containing the voltage fluctuations, improve load power factor and also voltage profile.

In this paper, a novel method for solving DS reconfiguration with SVCs planning problem is suggested. The proposed method establishes a tradeoff between security indexes (voltage stability security margin), power losses, installation cost and voltage deviation simultaneously for reconfiguration problem as a multi-objective nonlinear optimization problem. This method uses the new voltage stability index for DS voltage stability analysis, P_{sys} (Maximum loadability Limit), which is maximum loading of DS under the feasibility of power flow equations. The proposed method used HSA to solved mentioned optimization problem as the first layer of optimization search. HSA has emerged as a useful tool for engineering optimization which has been used in complex optimization problems. Hence, the optimal situations for open switches allocation and SVCs planning are determined to obtain the best objective. Due to the nature of this problem, the feasible topologies in reconfiguration are too important. To find best reconfiguration, it has been used the Matroid theory based on graph concept.

For each feasible reconfiguration pattern, the voltage stability index is calculated with considering SVCs based on non-linear optimization. The analysis process is performed using a steady state voltage stability index, P_{sys}, which is maximum loading under the feasibility of power flow equations [14-19]. Hence, a toolbox has been developed to assess the power system voltage stability margin based on Lagrangian method. The IEEE-33 and IEEE-69 bus distribution test systems are used to illustrate the performance of the proposed methodology.

II. SVC MODEL

In order to present the problem formulation, a brief view of the SVC model and the way it influences the distribution network is given in this section. Regarding to the behavior of static voltage stability phenomena, the SVC is modeled by a shunt variable reactive source and can be placed at the terminal bus in the mentioned study. Considering the SVC without losses and it can take values in a pre-specified range (usually between 0 and the maximum SVC capacity studied, here 600KVAr). Equivalent circuit of a SVC is shown in Figure 1.

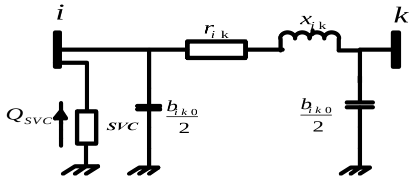

Figure 1. Equivalent circuit of a SVC connected to a bus terminal

III. PROBLEM FORMULATION

A. The Objective Function

Several aspects might be taken into consideration when defining the objective function of the network reconfiguration problem with SVCs planning. The objects which considered in this study, for finding optimal reconfiguration of DS via optimum planning of SVCs are minimizing total system power losses, maximizing loadability limit, minimum voltage deviation and minimizing the investment costs.

These objectives are discussed as follows:

B. Minimize the Active Power Losses

One of the significant benefits offered by reconfiguration and SVCs planning is reduction in losses. With the inclusion of optimum reconfiguration, line loss in the distribution system can be reduced. Power losses can be formulated as follow:

$$P_{loss} = \sum_{l=1}^{b} R_l I_l^2 = \\ = \sum_{i,j=1,2,\ldots,N_B} [V_i^2 + V_j^2 - 2\, V_i V_j \cos(\delta_i - \delta_j)]\; Y_{ij} \cos\varphi_{ij} \qquad (1)$$

where b is the number of branches, R_l is the resistance of line l, I_l is the current passing through line l, N_B is the number of buses, V_i and δ_i are the voltage magnitude and voltage angle of node i and, Y_{ij} and φ_{ij} are the magnitude and angle of the i-j line admittance. To aim active power losses in DS, it is necessary to calculate voltage magnitude and voltage angle of each node. For this calculation, it is used a load flow model. This model is based on graph theory and used graph topology of system. For gain to power flow converge, it is used the algorithm in [20]. By detecting voltage magnitude and voltage angle of each node, active power losses are calculated by Equation (1).

C. Maximizing Loadability Limit Index

Loadability limit is a new index to determine static voltage stability of DS [17]. System loadability can be evaluated by means of non-linear optimization which it tries to maximize system loading under the constraint of power flow equations. For this purpose, the problem can be formulated as follows [15-19]:

$$\min \quad : -P_{sys} \\ \text{s.t.} \quad : \begin{cases} P_{Gi} - P_{Di} - f_i(v,\delta) = 0 \\ Q_{Gi} - Q_{Di} - g_i(v,\delta) = 0 \end{cases} \qquad (2)$$

where P_{sys} is the system total active load, P_{Gi} and Q_{Gi} represent vectors of active and reactive generation (DGs and sub-transmission system), P_{Di} and Q_{Di} represent vectors of active and reactive load f_i and g_i are active and reactive power flow equations; respectively.

The main constraint for voltage stability is feasibility of power flow solution, therefore above equation tries to find maximum loading under the feasibility of power flow equation which corresponds to system loadability limit. This nonlinear problem can be solved by the Lagrange method. For this purpose, the non-constrained Lagrange function can be constructed as follows:

$$L = -P_{sys} + [\lambda]^T [P_G - P_D - f(V,\delta)] + \\ +[\gamma]^T [Q_G - Q_D - g(V,\delta)] \qquad (3)$$

In this optimization problem, increase pattern of loads at buses is one of the main factors, which dominates the loadability limit. So in order to include their effects; it can be modeled as follows [17]:

$$P_{Di} = \left[P_{Di}^{(0)} + \beta_i Pf_i (P_{sys} - P_{sys}^{(0)}) \right] \left(\frac{V_i}{V_i^{(0)}} \right)^{kpvi} \\ Q_{Di} = \left[Q_{Di}^{(0)} + \beta_i Qf_i (P_{sys} - P_{sys}^{(0)}) \right] \left(\frac{V_i}{V_i^{(0)}} \right)^{kqvi} \qquad (4)$$

where $P_{Di}^{(0)}$ and $Q_{Di}^{(0)}$ are the primary values of active and reactive load powers, α_i is generation contribution of each bus, β_i is generation and load contributions for each buses, Pf_i and Qf_i are load factor coefficients, $V_i^{(0)}$ is the primary value of bus voltage magnitude, V_i is the value of bus voltage, kpv_i and kqv_i are load active and reactive powers, $P_{sys}^{(0)}$ is the total primary active load of system and P_{sys} is the total active load of system. Hence the Lagrange equation can be finalized as Equation (5).

$$L : -\sum_{i=2}^{NB} \left[P_{Di}^{(0)} + \beta_i Pf_i (P_{sys} - P_{sys}^{(0)}) \right] \left(\frac{V_i}{V_i^{(0)}} \right)^{kpvi} + \\ \sum_{i=2}^{NB} \lambda_i \left\{ \alpha_i P_{sys} - \left[P_{Di}^{(0)} + \beta_i Pf_i (P_{sys} - P_{sys}^{(0)}) \right] \left(\frac{V_i}{V_i^{(0)}} \right)^{kpvi} - f_i(v,\delta) \right\} + \\ \sum_{i=2}^{NB} \gamma_i \left\{ Q_{Gi} - \left[Q_{Di}^{(0)} + \beta_i Qf_i (P_{sys} - P_{sys}^{(0)}) \right] \left(\frac{V_i}{V_i^{(0)}} \right)^{kqvi} - g_i(v,\delta) \right\} \qquad (5)$$

To solve Lagrange equation, the Newton-Raphson method is employed. For this purpose, the first derivatives of Lagrange equation are calculated as follows:

$$F_X = \frac{\partial L}{\partial X} = 0 \\ X = [V, \delta, \lambda, \gamma, P_{sys}] \qquad (6)$$

For example, F_{λ_i} can be derived as:

$$F_{\lambda_i} = \alpha_i P_{Sys} - \left[P_{Di}^{(0)} + \beta_i Pf_i (P_{Sys} - P_{Sys}^{(0)}) \right] - \\ -V_i \sum_{m=1}^{n_b} Y_{im} V_m \cos(\delta_i - \delta_m - \varphi_{im}) = 0 \qquad (7)$$

where n_b is the system bus numbers. Other equations also derived with same manner. Then, factors of every equation is calculated that contains ΔV, $\Delta\delta$, $\Delta\lambda$, $\Delta\gamma$ and P_{sys} by derivative of Equation (6) with these factors, for example the other equations can be derived as Equation (8).

In this study, factors of every equation are calculated which contains ΔV, $\Delta\delta$, $\Delta\lambda$, $\Delta\gamma$ and P_{sys}. By derivative of each Equation (7) with these factors, objective matrix would be earned as Equation (9). The proposed method is implemented using MATLAB platform and FORTRAN 95.

$$
\begin{aligned}
&\frac{\partial F_{\lambda j}}{\partial X}\Delta \mathrm{X}=\left\{-\alpha_j+\beta_j Pf_j\right\}\Delta P_{Sys}+\\
&\left\{V_j Y_{jj}\cos(\varphi_{jj})+\sum_{m=1}^{NB}Y_{jm}V_m\cos(\delta_j-\delta_m-\varphi_{jm})\right\}\Delta V_j\\
&+\left\{V_j\sum_{\substack{i=2\\ i\neq j}}^{NB}Y_{ji}\cos(\delta_j-\delta_i-\varphi_{ji})\Delta V_i\right\}\\
&-\left\{V_j\sum_{\substack{m=1\\ m\neq j}}^{NB}Y_{jm}V_m\sin(\delta_j-\delta_m-\varphi_{jm})\right\}\Delta\delta_j\\
&+\left\{V_j\sum_{\substack{i=2\\ i\neq j}}^{NB}Y_{ji}V_i\sin(\delta_j-\delta_i-\varphi_{ji})\Delta\delta_i\right\}
\end{aligned}
\tag{8}
$$

$$
\begin{bmatrix} F_V^{(0)}\\ F_\delta^{(0)}\\ F_\lambda^{(0)}\\ F_\gamma^{(0)}\\ F_{P_{Sys}}^{(0)} \end{bmatrix}
=
\begin{bmatrix}
F_{VV} & F_{V\delta} & F_{V\lambda} & F_{V\gamma} & F_{VP_{Sys}}\\
F_{\delta V} & F_{\delta\delta} & F_{\delta\lambda} & F_{\delta\gamma} & F_{\delta P_{Sys}}\\
F_{\lambda V} & F_{\lambda\delta} & F_{\lambda\lambda} & F_{\lambda\gamma} & F_{\lambda P_{Sys}}\\
F_{\gamma V} & F_{\gamma\delta} & F_{\gamma\lambda} & F_{\gamma\gamma} & F_{\gamma P_{Sys}}\\
F_{P_{sys}V} & F_{P_{sys}\delta} & F_{P_{sys}\lambda} & F_{P_{sys}\gamma} & F_{P_{sys}P_{sys}}
\end{bmatrix}
\cdot
\begin{bmatrix} \Delta V\\ \Delta\delta\\ \Delta\lambda\\ \Delta\gamma\\ \Delta P_{sys} \end{bmatrix}
\tag{9}
$$

The main steps of the loadability limit index calculation algorithm are given below:

```
Receiving Data $V,\ \delta,\ \lambda,\ \gamma,\ P_{sys}$
Repeat
    Make $Y_{bus}$ Matrix
    Calculate generation of sub-transmission system
    Make matrixes $J_{op}, L^{(0)}$
    Calculate $\Delta X = J_{op}\times L^{(0)}$ (Gause Elimination)
    Calculate $X_{new} = X_{old} + \Delta X$
Until (termination criteria are met)
```

D. Minimize the Voltage Deviations

To reach the best operational condition after SVCs installation, the voltage deviation term must be considered in objective function of nonlinear optimization problem too.

$$
v_{div}=\sum_{i=1}^{n}\left(\frac{V_{i\ ref}-V_i}{V_{i\ ref}}\right)^2 \tag{10}
$$

where $V_{i\ ref}$, V_i are desirable and real voltages of each bus, respectively.

E. Minimizing the Investment Costs

The SVC costs in installed are given as 40 US$/KVAr [21]. The main idea, in this optimization process, is to have best combinations of configuration (open switch selected via matroid theory) and optimal SVCs placement and size selection of SVCs. So that this configuration of DS must have maximum voltage stability, minimizes the voltage deviations, minimum real active power losses and minimize investment cost. The most simple topology representation for solving suggested program is to consider open switch number of DS and bus number and size of SVCs placement. Based on above discussion, the graphic process to finding optimal reconfiguration of DS and SVCs planning is shown in Figure 2.

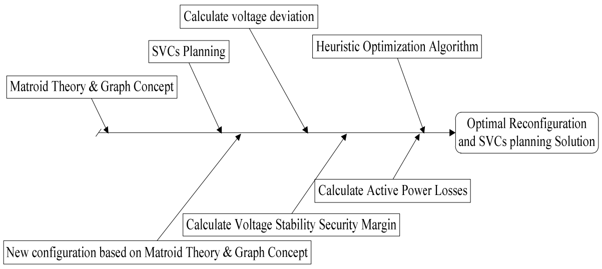

Figure 2. Graphic process to find optimal configuration

It is suggested two scenarios in this paper:

1. In the first scenario, only reconfiguration without any SVCs planning is considered. To find the best configuration of DS, three different objective functions are employed. The first and second one is based on single objective function. The objective function is how to minimize the active power losses and maximize voltage stability margin.

The problem is considered as a multi objective optimization in the third objective function. This objective function is minimizing the active power losses as well as improving the voltage stability margin. The overall objective function can be expressed as weighted sum of objective function as Equation (11).

$$
\begin{aligned}
&\text{minimize fitness}=k_1\times\hat{P}_{loss}+k_2\times\frac{1}{\hat{P}_{sys}}\\
&\hat{P}_{loss}=\frac{P_{loss}}{P_{loss-base}}\\
&\hat{P}_{sys}=\frac{P_{sys}}{P_{sys-base}}
\end{aligned}
\tag{11}
$$

where P_{sys}, $P_{sys\text{-}base}$ are total active load and the total active load of network without reconfiguration of DS, and P_{loss}, $P_{loss\text{-}base}$ are total active power loss and primary value of active load.

2. In this scenario, reconfiguration with SVCs planning is suggested. The objective function is calculated with below equation.

$$
\begin{aligned}
&\text{minimize fitness}=w_1\times\hat{cost}+w_2\times\hat{P}_{loss}+w_3\times\frac{1}{\hat{P}_{sys}}+w_4\times\hat{v}_{div}\\
&\hat{cost}=\frac{\sum_j cost_{SVC}(j)}{cost_{base}}\\
&\hat{P}_{loss}=\frac{P_{loss}}{P_{loss-base}}\\
&\hat{P}_{sys}=\frac{P_{sys}}{P_{sys-base}}\\
&\hat{v}_{div}=\frac{v_{div}}{v_{div-base}}
\end{aligned}
\tag{12}
$$

where $cost_{base}$ and $cost_{SVC}(j)$ are maximum SVC cost and installation cost of each SVC. This $cost_{base}$ is calculated when SVCs with their maximum capacity is used. v_{div}, $v_{div\text{-}base}$ are Voltage Deviations of system and primary Voltage Deviations of system.

The objective functions of the constrained scenario are: (1) voltage stability margin improvement (w_1=w_2=w_4=0), (Securest Reconfiguration and SVC Planning), (2) Mitigation of losses (w_1=w_3=w_4=0) (Minimum Loss Reconfiguration and SVC Planning), and (3) loss reduction, voltage stability margin improvement, minimization installation cost and minimize the voltage deviations (Coordinated Reconfiguration and SVC Planning Pattern).

The multi-objective function and the constraints are used to find optimum reconfiguration of DS and optimal SVCs planning with proposed objective function within the Harmony Search Algorithm and Particle Swarm Optimization which presented in following sections. Furthermore, an application of matroid and graph for these algorithms and proposed method are introduced.

IV. HARMONY SEARCH ALGORITHM

Harmony search algorithm was derived from the natural phenomena of musician's behavior when they collectively play their musical instruments (population members) to come up with a pleasing harmony (global optimal solution). This state is determined by an aesthetic standard (fitness function). The HS algorithm, is simple in concept, few parameters, and easy in implementation, has been successfully applied to various benchmarking, and real-world problems like traveling salesman [22].

HSA are explained in detail. In each step, related constraints are taken into account while finally the objective function associated with all constraints is minimized via HSA. The HSA search algorithm is applied to solve the feeder configuration problem and SVC planning using the following steps:

- Step 1: Initialize the optimization problem and algorithm parameters (HMS, PAR, HM, NI and etc).
- Step 2: Initialize the HM.

The format of the solution vector in HM matrix is given in Figure 3 and Figure 4. These figures explain format of solution vector for scenario 1 and 2, respectively. In the first scenario, HMS consists of configurations (suggested open switches with matroid and graph theory). In the second scenario, HMS consists of configurations with size selection and SVCs location in DS.

Switch statues (Number of Open Switch, *OS*)					Fitness value
OS_1	OS_2	…	OS_{n-1}	OS_n	

Figure 3. Format of the solution vector for first scenario

Switch statues (Number of Open Switch)					SVC planning		Fitness value
					SVC place	SVC size	
OS_1	OS_2	…	OS_{n-1}	OS_n	…	…	

Figure 4. Format of the solution vector for second scenario

In this step, the part of switch selection of HM matrix is filled with spanning tree theory. Spanning tree is a theory that has been explained by Kruskal [23]. It will be taken a base of Matroid to be a spanning tree of *G*. The following is a definition of a spanning tree. If *G* be a graph with n vertices, a spanning tree is a connected sub-graph that uses all vertices of *G* that has *n*-1 edges.

Because it can be taken the spanning trees of a graph to be the bases of a Matroid, it can conclude that the bases of a Matroid have the same number of elements, and by the definition of a spanning tree has *n*-1 elements (if there are n vertices).

- Step 3: Improvise a new harmony.
- Step 4: Update harmony memory: if the New Harmony vector has better fitness function that the worst harmony in the HM, the replaces the worst harmony in HM.
- Step 5: Check stopping criterion: terminate when the stopping criterion has been met.

PSO algorithm is applying to verify the result of HSA. The typical PSO algorithm is described in detail in [24].

V. APPLICATION OF MATROID THEORY TO HSA AND PSO

Matroid theory, initially developed by Whitney [25], the Matroid theory abstracts the important characteristic of matrix and graph theories. A definition and detail is given in [25]. A Matroid *M* consists of a non-empty finite set *E* and a non-empty collection *B* of subsets of *E*, called bases, satisfying the following properties:

(i): no base properly contains another base;

(ii): if B_1 and B_2 are bases and if e is any element of B_1, then there is an element of B_2 such that $(B_1\text{-}\{e\})\bigcup\{f\}$ is also a base.

The ii is known as the exchange property. This property states that if an element is removed from B_1, then there exists an element in B_2, such that a new base, B_3 is formed when that element is added to B_1. It can be used the property ii to show that every base in a Matroid has the same number of elements.

Matroid theory had been used to define *bw* in HSA and updating swarm in PSO. For reconfiguration problem, this operation means one of several edges are exchange between two spanning tree for a DS graph. Let be a graph with the vertices set and the edge set. The co-cycle is composed by all branches that connect the isolated nodes (loads) to the rest of graph (electric network) [26].

VI. RESULTS AND DISCUSSIONS

The proposed methodology is implemented on standard IEEE 33 and 69-bus DS. As these two cases studies are not such a large scale system, a single SVC is planned to install in.

The implementation of HSA and PSO is given below: For the study system IEEE 33 and 69-bus DS, the goal of the optimization is to find the best generation of the optimization is to find the best generation for these bus systems. The HMS is selected to be 20. HMCR and evaluation number are set to 0.9 and 100, respectively in

HSA. The PAR increase linearly from 0.44 and 0.99. Each harmony in the population is evaluated using equation (11) and (12) searching for harmony associated with min fitness.

As results of this paper are compared with other author’s result, the parameter in PSO must be tuned with other paper. These parameters control the impact of the previous velocities on the current velocity where, based on the reference 1, c_1 and c_2 are set to 1.4, w decrease linearly from 0.9 to 0.1. To find the minimum fitness, the HSA and PSO are run for 100 independent runs under different random seeds.

A. Case Study 1: IEEE 33-Bus Test System

This distribution network consists of 33 buses and 5 tie lines. The normally open switches are 33, 34, 35, 36, and 37 .For this base case, the total loads at feeder head-section are 3932.9450kW and 2448.2604 kVAr [1].

Scenario 1: The results of running HSA and PSO for different terms of objective function and results are derived as Tables 1 and 2. The results of the proposed method and other previous methods are shown in Table 3 for showing improvements of this method in compare with others. It is clear that the saving in total loss by the proposed method is better than all other methods.

In this paper, 2 objects are considered in fitness function for reconfiguration which is considering Matroid theory. This causes that all feasible patterns for switching status are considered in this study. Hence, switching statuses via Matroid and graph theory affect to find optimum reconfiguration.

The results for initial condition (without reconfiguration) are showing as column 1 of Tables 1 and 2. The results for improving voltage stability security index as objective function are derived as column 2 of Tables 1 and 2. Five (7, 10, 14, 16, 37)-switches in HSA and (7, 9, 14, 15, 28)-switches in PSO are obtained for opening on five bus ties in this case. These results show improvement in voltage stability margin (loadability limit) with these obtained switching statuses for reconfiguration.

Column 3 of Tables 1 and 2 are presented results for reduction power losses as objective function. (5, 8, 13, 31, 37) are switching statuses which are candidate for opening. Most of authors are used reducing power losses as objective function in previous literatures; these results are compared with proposed method in Table 3. The best result was reported in [20] which the result of reconfiguration with proposed method has better saving in total active losses. This result emphasis usefulness and robustness of mixing Matroid and graph theory via heuristic algorithm for reconfiguration.

Trade of between security improvement and loss reduction is another objective for reconfiguration in DS which are derived as column 4 of Tables 1 and 2. In HSA, five (5, 8, 13, 31, 24)-switches are obtained for opening five bus ties in this case for improving voltage stability index and reducing power losses. In This case HSA has 59.86% and 43.73% improvement in voltage stability and power losses, respectively.

By using PSO algorithm, five (6, 8, 14, 17, 24)-switches are candidate for opening. This DS configuration improves 66.14% and 41.29% improvement in voltage stability index and power losses, respectively.

Scenario 2: The results of running HSA and PSO for different terms of objective function and results are derived as Tables 4 and 5. One fixed SVCs planning with switches status are given in Tables 4 and 5.

The results for initial condition (without reconfiguration) are showing in column 2 of Tables 4 and 5. The results for improving voltage stability security index as objective function are derived as column 3 of Tables 4 and 5. It clearly observes that mixing SVC planning with reconfiguration problem has 30.38 percent improvement in voltage stability margin in comparing with only reconfiguration problem (comparing column 3 of Tables 1 and 4).

These results show improvement in voltage stability margin (loadability limit) with these obtained switching statuses for reconfiguration and these size selection and location of SVC. Colum 4 of Tables 4 and 5 is presented results for reduction power losses as objective function. 8 is candidate location of SVCs with maximum size.

Also IEEE 33-bus test system has 25.7 percent improvement in loss reduction in compare of only reconfiguration problem (comparing Colum 4 of Tables 1 and 4). This result emphasis usefulness and robustness of mixing Matroid and graph theory via heuristic algorithm for reconfiguration.

Improvement voltage security, improve voltage deviation, loss reduction and minimizing installation cost is another objective for reconfiguration in DS which are derived as Colum 5 of Tables 4 and 5. Bus 5 is SVCs placement with 404.86 kVAr size selections and (7, 11, 14, 32, 37) opened switches are obtained in this case for improving voltage stability index, reducing power losses and minimizing SVCs installation cost.

B. Case Study 2: IEEE 69-Bus Test System

The developed methodology is demonstrated by a radial distribution system with 69 buses, 7 laterals and 5 tie-lines [27]. For this base case, the total loads at feeder head- section are 3801.5 kW and 2694.6 kVAr.

Scenario 1: The results of running HSA and PSO for different terms of objective function and results are derived as Tables 6 and 7. The results of the proposed method are compared with other previous methods in Table 11.

From the result of this case study, it can be seen from the 69-bus test system that mixing Matroid and graph theory via heuristic algorithm for reconfiguration has the effects of loss reduction improvement over feeders in this particular case, and the configuration structures of optimum network with proposed reconfiguration are different from those without reconfiguration. Based on the 69-bus system with proposed reconfiguration, the proposed HSA and PSO methods in this paper has lower loss reduction than the method proposed in [27] (The best result was reported).

Tables 6 and 7 show the results of HSA and PSO, respectively. In This Tables HSA and PSO have 52.03% and 55.24% improvement in voltage stability and power losses, respectively.

Scenario 2: The results of running HSA and PSO for different terms of objective function and results are derived as Tables 9 and 10. From the result of this case study, it can be seen from the 69-bus test system that mixing Matroid and graph theory with heuristic algorithm for reconfiguration and SVC planning has the effects of loss reduction improvement over feeders, voltage stability margin improvement; minimization installation cost and minimize the voltage deviations. The configuration structures of network with proposed reconfiguration are different from Scenario1. Also this result that is given from mixing reconfiguration and SVC planning is better than only reconfiguration problem.

Table 1. Executing program via IEEE 33-bus via HSA (Scenario 1)

Objective Results Function	Initial condition	Securest Reconfiguration Pattern	Reconfiguration Pattern Based on Min. Loss	Coordinated Reconfiguration Pattern
Switch Status	33, 34, 35, 36, 37	7, 10, 14, 16, 37	5, 8, 13, 31, 37	5, 8, 13, 31, 24
Loadability Limit (P_{sys} (MW))	15.19	27.11	20.17	24.28
P_{sys} growth in compare with initial condition (%)	---	78.50	32.80	59.86
P_{loss} (KW)	210.99	139.92	97.17	118.73
P_{loss} reduction (%)	---	33.37	53.94	43.73

Table 2. Executing program via IEEE 33-bus via PSO (Scenario 1)

Objective Results Function	Initial condition	Securest Reconfiguration Pattern	Reconfiguration Pattern Based on Min. Loss	Coordinated Reconfiguration Pattern
Switch Status	33, 34, 35, 36, 37	7, 9, 14, 15, 28	5, 8, 13, 31, 37	6, 8, 14, 17, 24
Loadability Limit (P_{sys} (MW))	15.19	27.31	20.17	25.24
P_{sys} growth in compare with initial condition (%)	---	79.77	32.80	66.14
P_{loss} (KW)	210.99	151.58	97.17	122.54
P_{loss} reduction (%)	---	28.16	53.94	41.92

Table 3. Comparison proposed method with other methods using 33-bus system data (Scenario1)

Method	Final open switches	Total loss savings (%)
Proposed (HSA & PSO)	5, 8, 13, 31, 37	53.94
Ahmed R. Abul-Wafa [20]	34, 37, 11, 31, 28	48.07
M. Assadian [1]	7, 9, 14, 32, 37	31.39

Table 4. Executing program via IEEE 33-bus via HSA (Scenario 2)

Objective Results Function	Initial condition	Max. P_{sys}	Min. P_{loss}	P_{sys} P_{loss} *cost* V_{div}
Switch Status	33, 34, 35, 36, 37	7, 13, 16, 21, 26	5, 8, 11, 14, 29	7, 11, 14, 32, 37
SVC place (SVC size (KW))	---	9 (600)	8 (600)	5 (404.861)
P_{sys} (MW)	15.19	31.38	18.24	26.85
P_{sys} growth in compare with initial condition (%)	---	109.35	20.08	76.76
P_{loss} (KW)	210.99	121.62	42.95	102.63
P_{loss} reduction (%)	---	42.35	79.64	51.35
Min voltage magnitude (p.u) (bus number)	0.9129	0.9472 (18)	0.9526 (21)	0.9507 (32)
cost (K$)	---	24	24	16.194

Table 5. Executing program via IEEE 33-bus via PSO (Scenario 2)

Objective Results Function	Initial condition	Max. P_{sys}	Min. P_{loss}	P_{sys} P_{loss} *cost* V_{div}
Switch Status	33, 34, 35, 36, 37	7, 13, 17, 23, 30	5, 8, 11, 14, 29	7, 11, 14, 32, 37
SVC place (SVC size (KW))	---	12 (600)	8 (600)	5 (404.861)
P_{sys} (MW)	15.19	32.12	18.24	26.85
P_{sys} growth in compare with initial condition (%)	---	111.45	20.08	76.76
P_{Loss} (KW)	210.99	151.2	42.95	102.63
P_{loss} reduction (%)	---	28.34	79.64	51.35
Min voltage magnitude (p.u) (bus number)	0.9129	0.9325 (23)	0.9526 (21)	0.9507 (32)
cost (K$)	---	24	24	16.194

Table 6. Executing program via IEEE 69-bus via HSA (Scenario 1)

Objective Function Results	Initial condition	Securest Reconfiguration Pattern	Reconfiguration Pattern Based on Min. Loss	Coordinated Reconfiguration Pattern
Switch Status	69, 70, 71, 72, 73	17, 36, 44, 53, 62	16, 42, 43, 54, 62	16, 22, 42, 45, 53
Loadability Limit (P_{sys} (MW))	12.66	19.48	18.81	19.25
P_{sys} growth in compare with initial condition (%)	---	53.87	48.57	52.03
P_{loss} (KW)	20.89	13.03	9.19	9.35
P_{loss} reduction (%)	---	37.62	56.01	55.24

Table 7. Executing program via IEEE 69-bus via PSO (Scenario 1)

Objective Function Results	Initial condition	Securest Reconfiguration Pattern	Reconfiguration Pattern Based on Min. Loss	Coordinated Reconfiguration Pattern
Switch Status	69, 70, 71, 72, 73	19, 42, 45, 56, 61	16, 42, 43, 54, 62	16, 22, 42, 45, 53
Loadability Limit (P_{sys} (MW))	12.66	19.48	18.81	19.25
P_{sys} growth in compare with initial condition (%)	---	53.87	48.57	52.03
P_{loss} (KW)	20.89	12.22	9.19	9.35
P_{loss} reduction (%)	---	41.50	56.01	55.24

Table 8. Comparison proposed method with other methods using 69-bus system data (Scenario 1)

Method	Final open switches	Total loss savings (%)
Proposed (HSA & PSO)	16, 42, 43, 54, 62	56.01
A.Y. Abdelaziz [27]	14, 44, 50, 65, 70	55

Table 9. Executing program via IEEE 69-bus via HSA (Scenario 2)

Objective Function Results	Initial condition	Max. P_{sys}	Min. P_{loss}	P_{sys} P_{loss} $cost$ V_{div}
Switch Status	69, 70, 71, 72, 73	23, 35, 43, 47, 70	18, 45, 46, 60, 69	25, 35, 43, 52, 70
SVC place (SVC size (KW))	---	37 (600)	51 (600)	4 (337.07)
P_{sys} (MW)	12.66	28.50	18.90	21.74
P_{sys} growth in compare with initial condition (%)	---	125.11	49.29	71.72
P_{loss} (KW)	20.89	16.83	8.55	9.16
P_{loss} reduction (%)	---	19.44	59.07	56.15
Min. voltage magnitude (p.u) (bus number)	0.9724	0.9734 (65)	0.9851 (65)	0.9754 (65)
cost (K$)	---	24	24	13.48

Table 10. Executing program via IEEE 69-bus via PSO (Scenario 2)

Objective Function Results	Initial condition	Max. P_{sys}	Min. P_{loss}	P_{sys} P_{loss} $cost$ V_{div}
Switch Status	69, 70, 71, 72, 73	35, 43, 52, 70, 73	18, 45, 46, 60, 69	25, 35, 43, 52, 70
SVC place (SVC size (KW))	---	37 (600)	51 (600)	4 (337.07)
P_{sys} (MW)	12.66	26.55	18.90	21.74
P_{sys} growth in compare with initial condition (%)	---	109.72	49.29	71.72
P_{loss} (KW)	20.89	18.66	8.55	9.16
P_{loss} reduction (%)	---	10.67	59.07	56.15
Min. voltage magnitude (p.u) (bus number)	---	0.9631 (65)	0.9851 (65)	0.9754 (65)
cost (K$)	---	24	24	13.48

VII. CONCLUSIONS

This paper presents a reliable and efficient method approach towards reconfiguration and SVCs planning for voltage stability improvement and losses reduction by using a harmony search algorithm and particle swarm algorithm. Also, it has been presented a novel approach to combined reconfiguration and SVCs planning. In this paper a useful toolbox has been developed to calculated static voltage stability margin.

The proposed method has been successfully applied to a standard IEEE 33 and 69-bus DS. The results also can offer the usefulness of the proposed method which can consider as a practical technique. The results shown that the PM has the following merits in both reconfiguration problems and SVCs planning: efficient searching ability, robustness in result.

NOMENCLATURES

b: number of branch
B: current passing through line
$BIBC$: relation matrix between bus current injection and branch current
$BCBV$: relation matrix between branch current and bus voltage
$cost_{base}$: maximum SVC cost
$cost_{SVC}$: installation cost of each SVC
DLF: relation matrix between bus current injection and bus voltage
$F_V^{(0)}$: first derivative of Lagrange function by value of bus voltage magnitude
F_{VV} : derivative of F_V by value of bus voltage magnitude
If_{max}: maximum limit of generator exciting current
kpv_i : load active power
kqv_i : load reactive power
Pf_i : load factor coefficient
P_i : active power flow
P_{Di} : active load
$P_{Di}^{(0)}$: primary value of active load
P_{Gi} : active generation
$P_{Gi}^{(0)}$: primary value of active generation
P_{sys} : total active load of system
$P_{sys-base}$: total primary active load of system
P_{loss} : total active power loss
$P_{loss-base}$: total primary active power loss
Qf_i : load factor coefficient
Q_i : reactive power flow
Q_{Di} : reactive load
$Q_{Di}^{(0)}$: primary value of reactive load
Q_{Gi} : reactive generation
$Q_{Gi}^{(0)}$: primary value of reactive generation
R_l : resistance of line l
V_i : value of bus voltage magnitude
V_{div} : voltage deviations
$V_{div-base}$: primary voltage deviations of system
Y_{ij} : magnitude of the i-j line admittance
Z_{ij} : impedance of line between bus i and j
α_i : generation contribution of each bus
β_i : load contribution of each bus
γ : Lagrange multiplier
λ : Lagrange multiplier
δ_i : bus voltage angle
φ_{ij} : angle of the i-j line admittance

REFERENCES

[1] M. Assadian, M.M. Farsangi, H. Nezamabadi-pour, "GCPSO in Cooperation with Graph Theory to Distribution Network Reconfiguration for Energy Saving", Energy Conversion and Management, Vol. 51, pp. 418-427, 2010.

[2] B. Enacheanu, B. Raison, R. Caire, O. Devaux, W. Bienia, N. Hadj Said, "Radial Network Reconfiguration Using Genetic Algorithm Based on the Matroid Theory", IEEE Trans. on Power System, Vol. 23, pp. 186-195, 2008.

[3] G.K. Viswanadha Raju, P.R. Bijwe, "Efficient Reconfiguration of Balanced and Unbalanced Distribution Systems for Loss Minimization", IET Gener. Transm. Distrib., Vol. 2, pp. 7-12, 2008.

[4] A. Saffar, R. Hooshmand, A. Khodabakhshian, "A New Fuzzy Optimal Reconfiguration of Distribution Systems for Loss Reduction and Load Balancing Using Ant Colony Search-Based Algorithm", Applied Soft Computing Journal, Vol. 11, pp. 4021-4028, 2010.

[5] S. Jazebi, S.H. Hosseinian, B. Vahidi, "DSTATCOM Allocation in Distribution Networks Considering Reconfiguration Using Differential Evolution Algorithm", Energy Conversion and Management, Vol. 52, pp. 2777-2783, 2011.

[6] M.A. Kashem, V. Ganapathy, G.B. Jasmon, "Network Reconfiguration for Enhancement of Voltage Stability in Distribution Networks", Generation, Transmission and Distribution, IEE Proceedings, Vol. 147, pp. 171-175, 2000.

[7] B. Venkatesh, R. Ranjan, H.B Gooi, "Optimal Reconfiguration of Radial Distribution Systems to Maximize Loadability", IEEE Transactions on Power Systems, Vol. 19, pp. 260-266, 2004.

[8] M.A.N. Guimaraes, J.F.C. Lorenzeti, C.A. Castro, "Reconfiguration of Distribution Systems for Stability Margin Enhancement Using Tabu Search", Proc. of Power System Technology, International Conference on PowerCon., pp. 1556-1561, 2004.

[9] M. Arun, P. Aravindhababu, "A New Reconfiguration Scheme for Voltage Stability Enhancement of Radial Distribution Systems", Energy Conversion and Management, Vol. 50, pp. 2148-2151, 2009.

[10] N.C. Sahoo, K. Prasad, "A Fuzzy Genetic Approach for Network Reconfiguration to Enhance Voltage Stability in Radial Distribution Systems", Energy Conversion and Management, Vol. 47, pp. 3288-3306, 2006.

[11] J. Olamaei, T. Niknam, G. Gharehpetian, "Application of Particle Swarm Optimization for Distribution Feeder Reconfiguration Considering Distributed Generators", Proc. Applied Mathematics and Computation, pp. 575-586, 2008.

[12] Y.K. Wu, C.Y. Lee, L.C. Liu, S.H. Tsai, "Study of Reconfiguration for the Distribution System with Distributed Generators", IEEE Transactions on Power Delivery, Vol. 25 , pp. 1678-85, Jul. 2010.

[13] N. Rugthaicharoencheep, S. Sirisumrannukul, "Feeder Reconfiguration with Dispatchable Distributed

Generators in Distribution System by Tabu Search", Proc. Universities Power Engineering Conf. (UPEC), pp.1-5, 2010.

[14] M. Rezaie Estabragh, M. Mohammadian, M. Rashidinejad, "An Application of Elitist-Based Genetic Algorithm for SVC Placement Considering Voltage Stability", International Review on Modeling and Simulations (I.RE.MO.S.), Vol. 3, pp. 938-947, 2010.

[15] M.R. Aghamohammadi, M. Mohammadian, "Loadability Limit Assessment in Iran Power Network with Respect to Voltage Stability Constrains", Proc. of 11th International Power System Conference (PSC), Tehran, Iran, pp. 1-12, 1996.

[16] M.R. Aghamohamadi, M. Mohammadian, H.Saitoh, "Sensitivity Characteristic of Neural Network as a Tool for Analyzing and Improving Voltage Stability", Proc. of IEEE PES Trans. & Dist. Conference and Exhibition, Asia Pacific, pp. 1128-1132, 2002.

[17] M. Mohammadian, "Power System Voltage Stability and Security Assessment by Neural Network Technique", M.Sc. Dissertation, Dept. of Elect. Eng., K.N. Toosi University of Technology, Iran, Tehran, 1997.

[18] M. Mohammadian, M.R. Aghamohammadi, S.M.T. Bathaee, "Power Plants Generation Scheduling Constrained to Voltage Stability Limit Based on Sensitivity Characteristics of Neural Network", Proc. of 17th International Power System Conference (PSC), Tehran , Iran, pp. 1-10, 2002.

[19] M.R. Aghamohammadi, M. Mohammadian, A. Golkar, "Generation Scheduling Constrained to Voltage Stability Limit", Proc. of 16th International Power System Conference (PSC), Tehran, Iran, pp. 1-10, 2001.

[20] R. Abul-Wafa, "A New Heuristic Approach for Optimal Reconfiguration in Distribution Systems", Electric Power Systems Research, Vol. 8, pp. 282-289, 2011.

[21] A. Sode-Yome, N. Mithulananthan, "Comparison of Shunt Capacitor, SVC and STATCOM in Static Voltage Stability Margin Enhancement", International Journal of Electrical Engineering Education, Vol. 34, pp. 158-171, 2005.

[22] K. Nekooei, M.M. Farsangi, H. Nezamabadi-pour, "An Improved Harmony Search Approach to Economic Dispatch" International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 8, Vol. 3, No. 3, pp. 25-31, Sep. 2011.

[23] J.B. Kruskal, "On the Shortest Spanning Subtree of a Graph and the Traveling Salesman Problem", Proc. Amer. Math. Soc., Vol. 7, pp. 48-50, 1956.

[24] M. Mahdavi, H. Monsef, "Advanced Particle Swarm Optimization Used for Optimal Design of Single-Phase Induction Motor", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 2, Vol. 2, No. 1, pp. 55-59, Mar. 2010.

[25] H. Whitney, "On the Abstract Properties of Linear Dependence", American Journal of Mathematics, Vol. 3, pp. 509-33, 1935.

[26] J.A. Bondy, U.S.R. Murty, "Graph Theory with Applications", New York: Elsevier North-Holland, pp. 134-169, 1976.

[27] A.Y. Abdelaziz, F.M. Mohamed, S.F. Mekhamer, M.A.L. Badr, "Distribution System Reconfiguration Using a Modified Tabu Search Algorithm", Electric Power Systems Research, Vol. 80, pp. 943-953, 2010.

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