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POWER LOSS MINIMIZATION IN DISTRIBUTION SYSTEM BY USING NETWORK RECONFIGURATION AND SOLID STATE TRANSFORMER

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***Abstract*— In Electrical power systems, power losses in distribution networks contribute significantly. Reducing the network losses makes the power system more energy efficient. To achieve this, Network Reconfiguration and the Solid State Transformer (SST) is used in this paper. Network reconfiguration in distribution systems is aimed at finding a radial operating structure and is realized by changing the status of sectionalizing switches, and is usually done for loss reduction or for load balancing in the system, while satisfying operating constraints. The SST is primarily being considered as a replacement to the traditional Power frequency transformer. This paper proposes the ability of the dual-reactive power support feature of SST and Network Reconfiguration to reduce radial distribution network losses. Since it is a complex combinatorial optimization process, a Meta heuristic Harmony Search Algorithm (HSA) is used for this problem with an overall objective of reducing network losses. Along with this, voltage profile is also improved. The proposed algorithm was tested on a standard IEEE 33-bus radial distribution network for two different cases and implemented in Matlab 2018a and the results were shown.**

***Keywords* —Solid-state transformer, reactive power, Harmony search algorithm, Network Reconfiguration, VSI, Forward backward sweep load flow.**

1. INTRODUCTION

Electrical power losses in distribution networks have been a significant problem over past decades. Majority of Losses occurs in distribution systems compare to transmission system. In countries like India, 30 % losses occurs in distribution system [1]. Reducing losses in the network can contribute significantly in making the power system more energy efficient. Measures that have been proposed in literature to overcome losses range from Network reconfiguration to Usage of reactive power support devices. Reactive power devices used for loss reduction consists of capacitor banks to Custom power devices.

Capacitor Banks generate reactive power locally and improves voltage profiles in the network and consequently reduce the current flow leading to loss minimization [2]. However, reactive power injection by capacitor banks can't vary as the load changes.

To overcome these drawbacks, more flexible power electronics based solutions have been proposed. Distribution static compensators (DSTATCOM) [3] and Unified power quality conditioners (UPQC) [4] comes under this class. These can dynamically control reactive power flow as load changes and aids in reducing losses by minimizing branch currents and reactive power flow in the network and also to improve quality of power.

Recently Distributed generation (DG) became more popular and with the help power electronics based devices, they are used for reactive power support and generate real power locally results in power loss minimization. In [5], analytical expressions to optimally place DG units for maximum reduction of losses are developed.

Network reconfiguration entails changing the topological structure of distribution feeders by changing the open/close status of tie-line switches under both normal and abnormal operating conditions. Since many candidate-switching combinations are possible in a distribution system, finding the optimal network reconfigured system becomes a complicated combinatorial, non-differentiable constrained optimization problem. Distribution system reconfiguration for loss reduction was first proposed by Merlin and Back [6]. The drawback with this technique is the solution

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proved to be very time consuming. Several methods have been proposed to solve network reconfiguration. Other techniques based on the Branch Exchange are found in the works of [7]–[9].

Recently, the solid-state transformer which is a power electronics based distribution transformer has been an attracting interest. It is primarily being proposed as a lighter and more functional replacement to the present fundamental frequency transformer. SST has advantages like small size, fault tolerance, energy routing capabilities and reactive power support [10]-[12]. In [13] it introduces a Dual Reactive power support feature of SST and used to minimise the losses in radial distribution network. But the voltage profile of the system is not improved. To overcome this along with SST, network reconfiguration has been used in this paper.

In this paper, Harmony Search Algorithm (HSA) [14] is used to solve the distribution system network reconfiguration problem and to find location and rating for placement of Solid state Transformer (SST). The algorithm is tested on IEEE 33- Bus Distribution system.

The rest of this paper is organized as follows: Section II gives the SST overview, Section III provides Network Reconfiguration, Section IV gives overview of HSA algorithm, Section V explains the application of HSA to network reconfiguration problem and to find optimal location and rating of SST, Section VI presents results, and Section VII tells conclusion.

2. SST OVERVIEW

The SST is a power electronics based transformer that has multiple advantages such as improved power quality, smaller size, fault tolerance and reactive power support feature. The SST is being considered as a more functional replacement to the conventional transformer because of these advantages. The basic idea of the SST is to achieve the voltage transformation by medium to high-frequency isolation, therefore to potentially reduce the volume and weight of it compared with the traditional power transformer. The commonly used SST topology is shown in Fig. 1 and an overview on the each stage functions is given in Table- I.

Table I

SST Overview

Stage	Function	Input	Output	Active and reactive power
Stage-I	Controlled rectification	Medium voltage AC	High voltage DC	-Load active power -Grid reactive power support
Stage-II	DC-DC conversion	High voltage DC	Low voltage DC	-Load active power
Stage-III	Load Supply voltage	Low voltage DC	Low voltage AC	-Load active and reactive power

This paper utilizes reactive power support capabilities of both Stage-I and Stage-III inverters. Stage-I is capable of supporting grid reactive power ($Q_{sstgird}$) to regulate the load bus voltage, while stage-III supports the load reactive power demand ($Q_{sstload}$) locally. In this paper, this feature of SST is addressed as dual-reactive power support and is used to minimize the distribution system power losses.

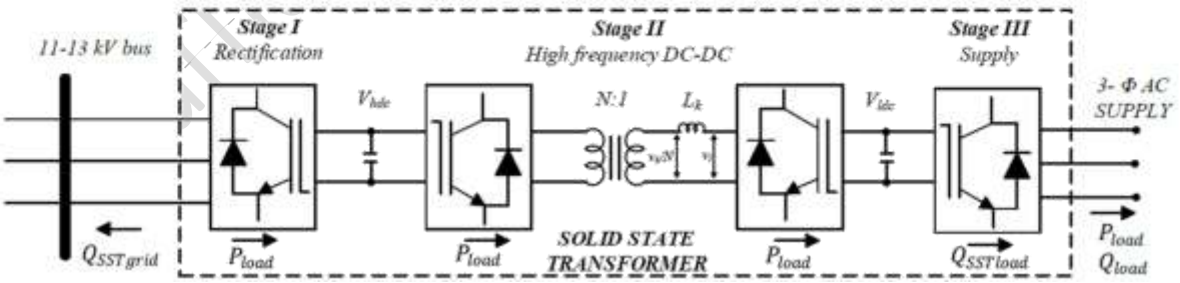

Fig. 1 Three Stage Solid State Transformer.

SST CONVERTER RATING:

The ratings of different stages of SST differ based on the power handled by them. Stage-III supports the complete load KVA power (S_{load}) and thus needs to be rated accordingly. However, stages-I and II support only the load active power and thus they are rated less than stage-III. In this paper, stage-I is used to provide reactive power support to the grid ($Q_{SSTgrid}$) and its converter is rated to handle the full load active power demand and the pre-determined level of reactive power support determined by Eq. (2). Thus stage-I converter rating can be determined as,

$$S_{stage1} = \sqrt{P_{load}^2 + Q_{sstgrid}^2} \quad (1)$$

Where P_{load} is the load active power demand and $Q_{sstgird}$ is the reactive power support to the grid. The summary of the converter ratings is shown in Table-II. In this paper, the level of $Q_{sstgird}$ will be determined by the percentage increase in apparent power rating of stage-I converter. If the rating of stage-I converter is m percent greater than the load active power demand, the grid reactive power capability ($Q_{sstgird}$) can be given as

$$Q_{sstgird} = \sqrt{(1 + 0.01m) \times P_{load})^2 - P_{load}^2} \quad (2)$$

Similarly, as part of the dual-reactive power feature of SST, the reactive power supplied to the load and not obtained from the network is given as,

$$Q_{sstload} = Q_L \quad (3)$$

Where, Q_L is the load reactive power demand. The above mentioned dual-reactive power feature of SST, where stage-I and stage-III are used for reactive power support distinguishes the SST from other reactive power support devices like STATCOM.

Table II
Converter Rating

In this paper, the SST may supply the entire load on a node or may partly supply a portion of the load. This is made under the assumption that remaining power is supplied by normal distribution transformer at the same node. Under this assumption, if an SST of rating y times the load rating x kVA is installed on a node with a power factor angle ϕ, the SST of rating $y.x$ kVA (S_{sst}) supplies the real and reactive power demand on the node as follows

$$S_{sst} = y.x \quad (4)$$

$$P_{sst} = y.x.cos\emptyset \quad (5)$$

Stage	Rating
Stage-1	$\sqrt{P_{load}^2 + Q_{sstgrid}^2}$
Stage-2	P_{load}
Stage-3	S_{load}

$$Q_{sstload} = \sqrt{(y.x)^2 - P_{sst}^2} \quad (6)$$

The dual-reactive power support feature in SST which is obtained from Eq. (2), changes the reactive power flow in the network and can be utilized to minimize losses and improve voltage profiles. The standard IEEE 33-bus distribution network shown in Fig. 2 is considered to implement the dual-reactive power support feature of SST.

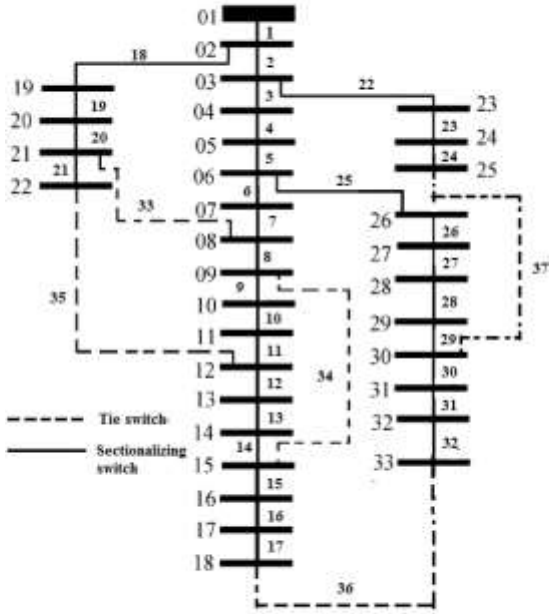

Fig. 2 33-Bus Distribution System

3. NETWORK RECONFIGURATION

In primary distribution systems, sectionalizing switches are used for protection, to isolate a fault in the system, and for network reconfiguration. In this paper, the Network Reconfiguration is done by using Network topology. Here we first define tree branches (line section) and links (tie-lines). After that we need to construct Bus incidence matrix (A). Now we split Bus Incidence matrix into two sub matrix, one matrix A_b which have elements corresponding to tree branches and other matrix A_l which have elements corresponding to links. Then we construct Branch path incidence matrix (K) using below equations,

$$A_b \times K^t = U \quad (7)$$

where U is an identity matrix

$$K^t = A_b^{-1} \quad (8)$$

Reference [15] gives more information on network topology. After finding Branch Path incidence matrix, we get line data of new reconfigured network from this matrix. Now in order to find optimal tie line switches, Harmony Search Algorithm is used.

IV. HARMONY SEARCH ALGORITHM

The HSA is a new meta-heuristic population search algorithm proposed by Geem *et al* , Das *et al.* [16] proposed an explorative HS (EHS) algorithm for many benchmarks problems successfully. HSA was derived from the natural phenomena of musicians' behaviour 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). HS algorithm is simple in concept, less in parameters, and easy in implementation. It has been successfully applied to various benchmark and real-world problems like traveling salesman problem. The main steps of HS are as follows:

1. Initialize the problem and algorithm parameters.
2. Initialize the harmony memory.
3. Improvise a new harmony.
4. Update the harmony memory.
5. Check the termination criterion.

Step 1. Initialization of Problem and Algorithm Parameters:

The general optimization problem is specified as follows:

Minimise f(x)

Subject to $x_i \in X$, *i =1,2,……N* (9)

Where f(x) is objective function; x is the set of the possible range of values for each decision variable x_i; N is the number of decision variables; X_i is the set of the possible range of values for each decision variable that is

$$x^{min} \leq X_i \leq x^{max} \tag{10}$$

Where x^{min} and x^{max} are lower and upper limits for each decision variable. The HS algorithm parameters are specified in this step. These are

HMS = Harmony memory size or the number of solution vectors in the harmony memory.

HMCR = Harmony memory considering rate.

PAR = Pitch adjusting rate.

BW = Band width.

NI = Number of improvisation or iterations.

The Harmony memory (HM) is a memory location where all the solution vectors (sets of all decision variables) are stored. Here HMCR and PAR are parameters which are used to improve the solution vector.

Step 2. Initialise the Harmony Memory:

In this step, the HM matrix is packed with as many randomly generated solution vectors. The matrix size is HMS × N

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & \cdots & x_{N-1}^1 & x_N^1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \tag{11}$$

The below equation is used for random initialisation,

$$x_j = x_j^{min} + rand(0,1) \times (x_j^{max} - x_j^{min}) \tag{12}$$

Step 3. Improvise a New Harmony:

A New Harmony vector is generated based on three criteria as shown below:

1) Memory consideration, (HMCR)

2) Pitch adjustment, (PAR) and

3) Random selection.

if ($rand_1(0,1) < HMCR$)

$x_j^{new} = x_j^a$ a ∈ 1,2,3……HMS

if ($rand_2(0,1) < PAR$)

$x_j^{new} = x_j^{new} + rand \times BW$

end if

else

$x_j^{new} = x_j^{min} + rand \times (x_j^{max} - x_j^{min})$

end if (13)

Step 4. Update Harmony Memory

After $X^{new} = \{x_i^1, x_i^2, \dots\dots\dots..x_1^{HMS}\}$ was obtained we calculate its fitness and it is compared with worst Harmony in HM. If the New Harmony vector has better fitness function than the worst harmony in the HM, the worst Harmony is replaced with the New Harmony in the HM matrix as shown below.

if $(f(X^{new}) < f(X^{worst})$

$X^{worst} = X^{new}$

end if (14)

Step 5. Check Termination Criterion

The HSA is terminated when the termination criterion (e.g., maximum number of improvisations) has been met. Otherwise, steps 3 and 4 are repeated.

5. APPLICATION OF HSA FOR POWER LOSS MINIMIZATION

This section describes application of HSA in network reconfiguration and SST installation problem for real power loss minimization and voltage profile improvement. Both reconfiguration and SST installation problems are complex combinatorial optimization problems. In this paper, these two problems are dealt using HSA. For reconfiguration problem, HM contains combination of open switches as solution vector and for SST problem, HM contains locations and Ratings of SST as solution vector. Initially HM is initialised randomly and updated as discussed in section IV.

A) PROBLEM FORMULATION:

The main objective of the proposed algorithm is to identify optimum network reconfiguration, the location and size of SST in a distribution network to achieve maximum reduction in losses. The objective can be written as

Objective function:

$$Minimise\ P_{loss} = \sum I_b^2 \times R_b \quad (15)$$

Where I_b and R_b are the branch currents and resistances respectively. The following were general constraints used.

Constraint 1:

$$S_{sst}(n) = \begin{cases} S(n) & if\ S(n) < S_{SSTmax} \\ S_{SSTmax} & if\ S(n) > S_{SSTmax} \end{cases} \quad (16)$$

$S(n)$ is load rating in KVA at n^{th} node

Constraint 2:

$$N_{SST}(n) = 1 \quad (17)$$

Where $N_{SST}(n)$ is number of SSTs installed at n^{th} node. The Maximum rating (S_{SSTmax}) and number of SSTs are predetermined. The rating and location of SSTs placed are updated at every iteration.

Application of HSA for loss minimization problem with reconfiguration and SST placement is illustrated with the help of standard IEEE 33-bus radial distribution system with base voltage 12.66-kV and Base MVA 100 MVA. In 33-bus system, in order to represent an optimal network topology, we need only the positions of open switches in the distribution network. The data for 33-Bus system is taken from [7]. The 33-Bus Distribution System consists of five tie lines and 32 sectionalize switches. The normally open switches are 33, 34, 35, 36, and 37, and the normally closed switches are 1 to 32 as shown in Fig. 2. The total real and reactive power loads on the system are 3715 KW and 2300 KVAR, respectively.

In this paper, Forward Backward sweep load flow algorithm [17] is used to find power loss. The Algorithm consists of two steps and is discussed below

STEP1-BACKWARD SWEEP:

In this step, the currents flowing in each node of the system are calculated .On the first iteration, all the voltages are set to one. The current in any node 'n' may be given as,

$$I_l(n) = \frac{(P_l(n) - Q_l'(n))}{V^*(n)} \quad (18)$$

$$where\ n = 1,2 \ldots .N$$

Where, N is the number of nodes in the network, P_l is load active power demand and Q_l' is the net reactive power demand and $V(n)$ and $I_l(n)$ is the voltage and load current at node n. When an SST is present at a specific node, the net reactive power requirement, at that node, will be based on the dual-reactive power support and the actual load reactive power requirement as per Eq. (2) and Eq. (6). This net reactive power requirement at node n can be expressed as,

$$Q_l'(n) = Q_l(n) - Q_{sstload} - Q_{sstgrid} \quad (19)$$

Where, $Q_{sstload}$ and $Q_{sstgrid}$ are part of the dual-reactive power support feature described earlier and Q_l is the actual load reactive power requirement at node n. If SST is not present at node n, as per Eq. (19) both $Q_{sstload}$ and $Q_{sstgrid}$ will be zero and thus,

$$Q_l'(n) = Q_l(n) \quad (20)$$

On obtaining the current in all the nodes in the system, the branch current flowing in each branch of the network are calculated as

$$I_b(sr) = I_l(r) + \sum I_b(rl) \quad (21)$$

$$where\ l = 1,2 \ldots \ldots N$$

Where I_b branch or line currents, s and r denotes sending bus and receiving bus of the line/ branch, $I_b(rl)$ is branch currents of line connected to receiving bus r.

STEP2- FORWARD SWEEP:

In this step, the currents obtained from the backward sweep are used to recalculate the voltages as,

$$V(r) = V(s) - I_b(sr) * Z(sr) \quad (22)$$

Where $Z(sr)$ is the branch Impedance. These voltages are then used to repeat the backward sweep until the solution converges. The power loss for Original system is 202.661-kW. The lowest bus bar voltage is 0.9131 p.u., which occurs at node 18.

Table III
HSA Parameters

B)

PARAMETERS	VALUE
HMS	100
HMCR	0.95
PAR	0.4
BW	0.0001
Number of iterations(NI)	1000

CASE STUDY:

Now we consider two scenarios where we place two SSTs and other, with three SSTs. The parameters of HSA are shown in Table III.

CASE-A: TWO UNITS

In this, we apply HSA simultaneously for both network Reconfiguration and SST placement. we place two SST unit, such that maximum rating of SST is 300-KVA and sum of ratings of two units is 500-KVA i.e.,

$$S_{SSTmax} = 300KVA \quad (23)$$

$$\sum_{j=1}^{2} S_{sst}(j) = 500\ KVA \quad (24)$$

CASE-B: THREE UNITS

In this case, first we apply Network Reconfiguration. To reconfigure the network, all possible radial structures of given network (without violating the constraints) are generated initially and optimum network is found and next we find buses with voltage less than 0.95 using Voltage sensitivity factor (VSF) [18] as shown below.

Voltage Sensitivity Factor (VSF) is the ratio of base case voltages, $V(n)$ at each node to 0.95 and can be calculated by

1. Compute normalized voltage, $Norm(n)$ for all load buses

$$Norm(n) = \frac{V(n)}{0.95} \quad (25)$$

2. Norm (n) < 1.000 is eligible for placing SST.

After that we place SST's at these buses to improve voltage profile. Here number of SST's used is '3'. The constraints are

$$S_{SSTmax} = 250 \quad (26)$$

$$0.95 \le V(n) \le 1.00 \quad (27)$$

$V(n)$ is Bus voltage at node n .

6. RESULTS AND DISCUSSION

The proposed algorithm was applied for IEEE 33-Bus distribution system. The Results for the two cases are discussed below. The Matlab 2018a is used to implement program.

CASE-A:

As discussed above, HSA is applied simultaneously for Network Reconfiguration and SST location and rating problem. The open switches obtained are 7, 14, 9, 32, 37 and SST sizes are 300 and 200-KVA at location 30, 32. Further the dual-reactive power feature is enabled by increasing the stage-1 converter rating by different percentage. The results are shown in Table IV.

Table IV
Case-A Two Units

Stage-1 reactive power rating (%)	SST location	SST Size (KVA)	Power loss (KW)	Tie line switches
-	-	-	202.661	33, 34, 35, 36, 37
0	30,32	300,200	116.704	7, 14, 9, 32, 37
10	30,32	300,200	111.407	7, 14, 9, 32, 37
15	30,32	300,200	110.327	7, 14, 9, 32, 37
20	30,32	300,200	109.417	7, 14, 9, 32, 37
25	30,32	300,200	108.658	7, 14, 9, 32, 37

The Voltage profile of original Network, and for Reconfigured network with SST placement is shown in Fig. 3. It shows clearly that voltage profile has improved.

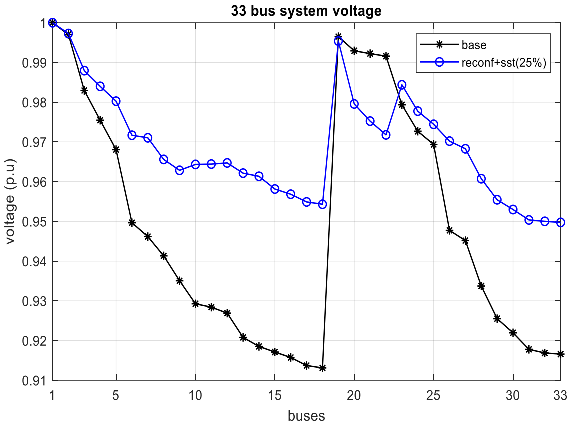

Fig. 3 Voltage profile at various buses of IEEE 33-Bus Distribution System (Case-A).

CASE B:

In this case, first we apply HSA algorithm for Network Reconfiguration. The optimal open switches obtained by the proposed algorithm is 7, 14, 9, 32, 37, which has a real power loss of 139.5513 kW. The minimum node voltage of the reconfigured system is 0.9378 p.u at bus 32. The Table V shows the results of Network reconfiguration.

Table V
Network Reconfiguration

S.no	Open Switches	Power loss	Minimum Voltage
Original System	33, 34, 35, 36, 37	202.66	0.91311
Reconfigured Network	7, 14, 9, 32, 37	139.551	0.9378

Fig. 4 shows the Reconfigured network. After obtaining new reconfigured network, we then find the buses whose VSI < 1. Buses 17, 18, 29, 30, 31, 32, 33 have VSI<1 and are selected for placement of SST. Here we place Three SST's. Again we apply HSA algorithm to find optimum location and SST rating. Further the dual-reactive power feature is enabled by increasing the stage-1 converter rating to different percentages. For this case, the minimum voltage occurs at bus 33 and for different Stage-1 reactive power rating (%) the results are shown in Table VI.

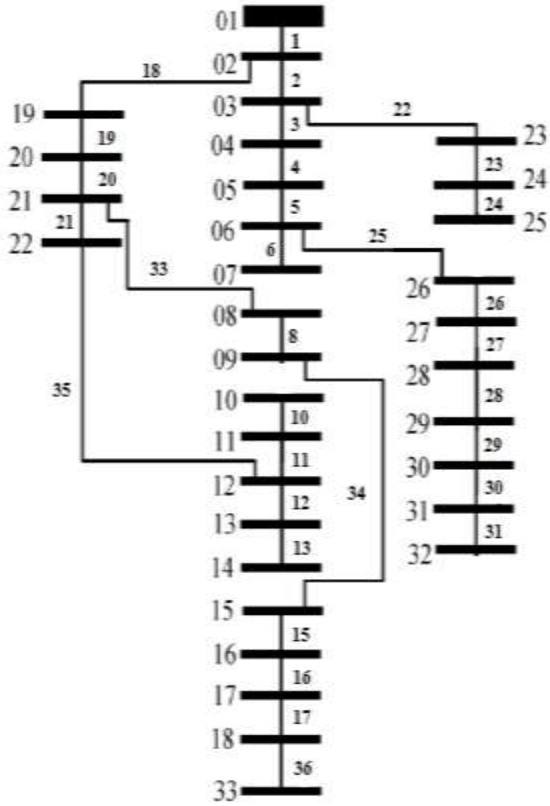

Fig. 4 Optimal network after Reconfiguration.

Table VI
Case-B Three Units

Stage-1 reactive power rating (%)	SST location	SST Size (KVA)	Power loss (KW)	Minimum Voltage (P.U)
0	30, 31, 32	250, 166, 233	114.974	0.94731
10	18, 30, 32	98, 250, 233	109.946	0.95108
15	18, 30, 32	98, 250, 233	108.503	0.95204
20	18, 30, 32	98, 250, 233	107.339	0.95288
25	18, 30, 32	98, 250, 233	106.379	0.95361

The Voltage profile of original Network, after reconfiguration and reconfiguration with SST is shown in Fig. 5. It shows clearly that voltage profile has improved.

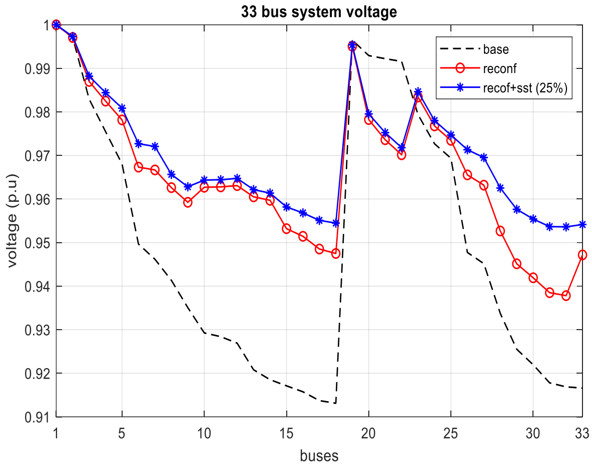

Fig. 5 Voltage profile at various buses of IEEE 33-Bus Distribution System (Case-B).

7. CONCLUSION

In this paper, the concept of Network Reconfiguration and dual-reactive power support feature of SST is used where SST supplies the load reactive power demand and also injects reactive power into the grid. This feature is used to reduce network losses in a radial distribution network and improve voltage profiles. As placing SST alone, voltage profile is not improved that much and requires large rating and more number of SST's which increases overall cost. To avoid this, network reconfiguration is used along with SST placement. In order to find reconfigured network, optimal size and locate the SST installation, HSA is used. Installing smaller units of lower rating may be more practical and viable with the current state of technology. The overall losses and voltage is improved compare to original system.

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