Voltage Control and Power Loss Reduction in an Active Distribution Network using Solid State Transformers

Syed Faizan Ali Shah[1], Intisar Ali Sajjad[2], Muhammad Faisal Nadeem Khan[3], Haroon Farooq[4], Akhtar Rasool[5], Farhan Qamar[6]

Abstract— **Power losses in a distribution network accounts for a major part of energy loss in the overall system. Reduction in power losses can make the power system more energy-saving. This paper analyzes the reactive power handling capabilities of Solid-State Transformer (SST) by adopting controls on both sides of SST. Moreover, a Moth swarm algorithm is used for selecting the optimal values of phase angles and modulation coefficients of the Voltage Source Converters (VSCs) on both sides of SST. Results show the better performance of the presented reactive power management scheme with regard to voltage violation and power loss of the system. Moreover, bidirectional power flow enables flexible operation of renewable energy sources (RES). Finally, the performance of the control scheme and optimization algorithm is investigated using a modified IEEE 33-bus system using MATLAB.**

Index Terms— **Moth Swarm Algorithm, Power Losses, Radial Distribution Network, Reactive Power, Solid State Transformer**

I. INTRODUCTION

In modern era, where the technological development has brought tremendous evolutions in the life of a common man, an alarming situation has also been created through the excessive use of energy. Under such conditions, meeting the demands of electricity with conventional sources of energy has turned into a challenging problem, hence there is need to generate electricity through unconventional means. Replacing conventional means of generation with renewable energy sources (RES) i.e. wind, photovoltaic (PV) systems brings many positive impacts to the environment, resulting in reduction of emission of carbon dioxide and other harmful gasses [1]. Renewable resources are not only eco-friendly, but also very efficient sources for electricity generation. In spite of promising benefits, large invasion of RES in the grid causes serious issues of voltage deviations and power losses [2]. However, these issues can be considerably reduced by using the reactive power compensation [3].

Many solutions have been proposed to address the shortcomings of RES through the management of reactive power. The most widely used devices to mitigate the voltage deviation and power loss problem includes on-load-tap-changers (OTLCs) and capacitor banks. Although OTLCs can effectively improve the power system stability but in order to supply reactive power compensation OTLCs require shunt VAR compensators and static VAR compensators, consequently increasing the cost of the system [4]. Another problem associated with OTLCs is fluctuations created through tap commutation under loading conditions, causing damage to material used for insulation and winding [5]. Similarly, the optimal location and size of capacitor banks also plays a vital role to enhance the system stability, but they occupy a large volume and are only used for a single purpose [6], [7]. In another research, synchronous generator was used as a reactive power compensation device, but the problem is that these devices perform efficiently when stationed closed to the entry point of distribution system, and thus have limited effect on voltage deviation and reactive power compensation in the system [8]. The standard transformer is not smart enough to meet the desired standards of rapidly progressing future renewable system architectures i.e., permitting bi-directional energy transfer, offering better grid linkage, embracing upgraded technologies, and maximizing the capacity to store energy, therefore it has to be replaced with electronically equipped solid state transformer (SST) [9].

SST is capable of providing additional benefits in contrast with customary transformer with regard to power quality and its abilities for reactive power management, regulation of voltage, and power factor improvement [10]. Along with many promising features, an SST has a very compact size because at high frequencies the requirement of transformer core and winding drop significantly [11], [12]. The first AC/AC power electronic transformer (PET) was introduced by W. Mc-Murray in 1970 [13]. But because of low power ratings and slow switching speed of the power electronics technology at that time, it could not be used in power system applications. However, with the recent developments in the area of power electronics, SST has been declared as one of ten turned out technologies shaping the future of smart grids [14]. In one research, a multi-pulse rectifier (12 pulse rectifier) based on medium frequency transformer was presented and compared with the conventional 12 pulse rectifier based on low frequency transformer [15]. The proposed approach was proved to be impressive in providing power density twice more than that of ordinary transformer by lowering the weight of transformer. To address the issues related to power quality,

[1]MSc Scholar, Department of Electrical Engineering, University of Engineering and Technology Taxila, Pakistan. syedfaizanalibukhari@yahoo.com
[2]Assistant Professor, Department of Electrical Engineering, University of Engineering and Technology Taxila, Pakistan. intisar.ali@uettaxila.edu.pk
[3]Assistant Professor, Department of Electrical Engineering, University of Engineering and Technology Taxila, Pakistan. faisal.nadeem@uettaxila.edu.pk
[4]Assistant Professor, Department of Electrical Engineering, University of Engineering and Technology Lahore, Pakistan. haroon.farooq@uet.edu.pk
[5]Assistant Professor, Department of Electrical Engineering, Sharif College of Engineering and Technology, Lahore, Pakistan. akhtar@sabanciuniv.edu
[6]Assistant Professor, Department of Telecommunication Engineering, University of Engineering and Technology Taxila, Pakistan. farhan.qamar@uettaxila.edu.pk

a transformer-less SST was presented. The proposed approach appeared beneficial in amplifying the power quality of the system by isolating the transient disturbances that arise from mismatch between loads and grid [16]. In a research, the problem related to voltage violation and reduction of load on high voltage side of grid has been achieved [17]. In another research the authors have realized the twofold reactive power support capabilities of SST to diminish active power losses in a distribution network, which was achieved through optimally locating the SST [18]. However, the paper lags in considering the influence of DGs on the distribution network. The problem of optimal dispatch of reactive power was considered using successive quadratic programing methodology with an objective to provide compromise among economic and security goals [19]. The optimal power flow algorithm was presented, by some investigators, using newton's approach [20]. The performance of presented technique was compared with the other methods by considering different aspects of system under analysis. Likewise, the optimal dispatch of reactive power equipped with the interior point method was presented. The proposed algorithm was tested on 1832 and 3467 bus systems to validate its performance [21]. In order to enhance the feature of reactive power support, many optimization techniques have been proposed to optimally select the control variables of SST in several studies, including linear/nonlinear programming, Newton's approach, quadratic programming, and the interior point method, but such techniques have inherent slow convergence rates and problems of trapping into the local optima. To minimize the problems associated with standard optimization algorithms, metaheuristic optimization algorithms have been developed. Recently, a paper proposed Metaheuristic algorithm to solve the voltage deviation and power loss problem using Moth flame optimization (MFO) [22], [23]. However, in the proposed algorithm, the moth may be distracted by artificial lights in the surrounding and hence, can diverge from the optimum solution.

Considering all the discussed gaps in research, this paper proposes the reactive power management solution based on SST using Moth swarm algorithm (MSA). The network model not only the impact of RES but also takes into account the internal losses associated with SST. Through efficiently optimized control variables of SST, i.e., phase angles and modulation coefficients of VSCs on both sides of SST, the network losses are minimized considerably and also an improvement in the voltage profile of the system can be seen. Besides this, the classification and updating of moths based on celestial navigation, Lévy mutation, and lateral positioning, accuracy and convergence rate of the algorithm can be improved.

The organization of remaining paper is as follows: Section II explains the mathematical models of different distribution system components; Section III outlines the power flow technique; Section IV presents the mathematical formulation of optimization problem; Section V is based on the discussion of the results and Section VI includes conclusion of the paper.

II. MATHEMATICAL MODEL OF THE SYSTEM

A. SST Model

In Fig. 1, the fundamental block diagram of SST is shown, it comprises of three major components, a primary side voltage source converter (VSC), a secondary end voltage-source converter (VSC) and a high frequency transformer. Both of the converters work on the principle of Pulse Width Modulation (PWM). The mathematical model of SST is developed using Fig. 2, where P_1 and Q_1 are the primary side active and reactive power. Similarly, P_2 and Q_2 are the real and reactive powers of secondary side. The primary and secondary reactance has been named as x_1 and x_2, whereas V_0 and V_s represent the voltage at the secondary side of SST and the distribution system voltage. V_{dc} are the voltage at the DC-Link between converters and C_1, C_2, δ_1, δ_2 are the coefficients of modulation and the phase angles on the either ends of the converters.
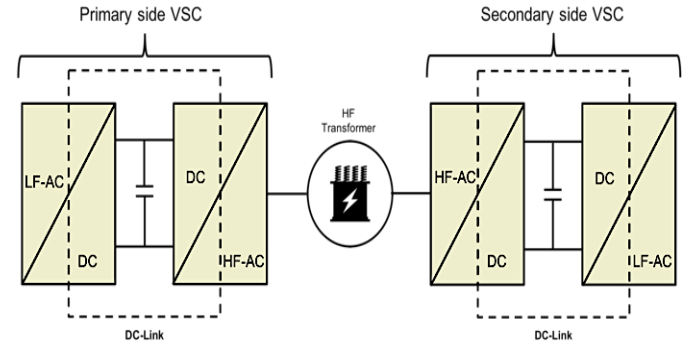

Fig. 1: SST Topological Diagram

Control adopted on both sides of SST can be represented by the equations (1-4).

$$V_{dc} = 2P_1 x_1 / C_1 V_s \sin \delta_1 \qquad (1)$$

$$Q_1 = V_s (V_s - C_1 V_{dc} \cos \delta_1 / 2) / x_1 \qquad (2)$$

$$V_0 = 2P_2 x_2 / C_2 V_{dc} \sin \delta_2 \qquad (3)$$

$$Q_2 = V_0 (C_2 V_{dc} \cos \delta_2 / 2 - V_0) / x_2 \qquad (4)$$

It can be noticed through the above equations that the reactive power and the voltage on the either sides of the SST can be controlled by adjusting the values of control variables C_1, C_2, δ_1 and δ_2.
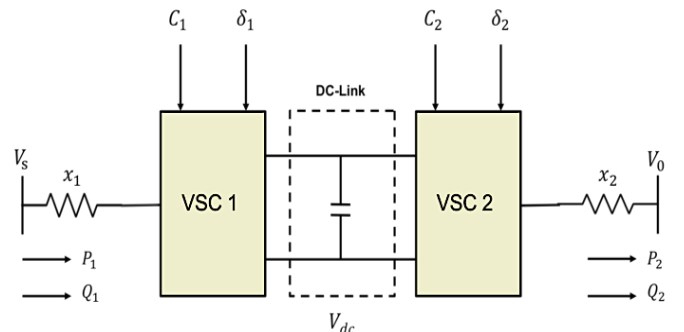

Fig. 2: SST Simplified Model

B. Photovoltaic (PV) Model

The probabilistic model of the solar irradiance is modelled using beta distribution as [24]:

$$f^t(r^t) = \frac{\gamma(\alpha^t + \beta^t)}{\gamma(\alpha^t).\gamma(\beta^t)} \left(\frac{r^t}{r_{max}}\right)^{\alpha^t-1} \left(1 - \frac{r^t}{r_{max}}\right)^{\beta^t-1} \qquad (5)$$

In equation (5), r_{max} is the maximum value of solar irradiance, γ is the gamma distribution function and t represent time instant, where α^t and β^t are the beta distribution shaping parameters.

Similarly, the output power of the PV system can be calculated as:

$$P_{PV} = \begin{cases} P_{rated} \times \frac{r}{r_{rated}}, & r \le r_{rated} \\ P_{rated}, & r > r_{rated} \end{cases} \qquad (6)$$

Where, P_{rated} is the rated power of PV system, r is the solar irradiance and r_{rated} represents the rated solar irradiance. The rated power of PV is 100KW, whereas the rated solar irradiance is taken as 500 W/m². The 24-hours irradiance pattern can be seen in the Fig. 3.
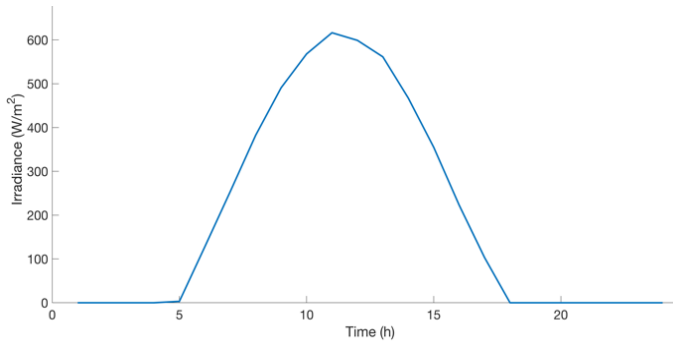

Fig. 3: Hourly Solar Irradiance

C. Wind Turbine Model

Likewise, the output active power and the probabilistic model of wind speed using Weibull distribution is modeled using the equations give below:

$$P_w = \begin{cases} 0, & v < v_{ci} \ or \ v \ge v_{co} \\ \frac{P_r \times v}{(v_r - v_{ci})} - v_{ci} & v_{ci} \le v < v_r \\ P_r & v_r \le v < v_{co} \end{cases} \qquad (7)$$

$$f^t(v^t) = \left(\frac{k^t}{v^t}\right)\left(\frac{v^t}{c^t}\right)^{k^t-1} exp\left(-\left(\frac{v^t}{c^t}\right)^{k^t}\right) \qquad (8)$$

Where, P_r is the rated wind power, k^t and c^t are the shaping parameters of Weibull distribution and v_r, v_{ci}, v_{co} are the rated, cut-in and cut-out speeds of the wind. The rated wind power is taken to be 100KW, whereas the rated, cut-in and cut-out wind speeds are 14, 3.5 and 25 m/sec. The hourly wind speed used for wind power generation is shown in the Fig. 4.
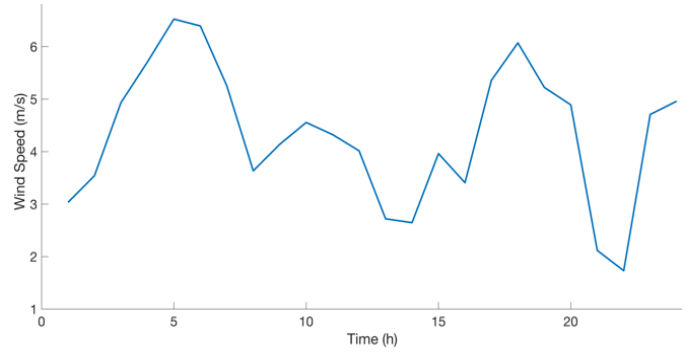

Fig. 4: Hourly Wind Speed

D. Load Model

Considering the 24-hours demand of consumers, the load at each node of the system is categorized into three types: Residential load, Commercial load and Industrial load [25]. By considering the load distribution in 24-hours and the proportion of all types of loads in the system, the load can be modelled as:

$$Load_{i,j} = \sum_{j=1}^{3} LT_{j,i} \times LP_{i(max)} \times D_{j,h} \qquad (9)$$

The subscripts i, j, h represent the number of nodes, types of loads and hours respectively. Where $LT_{j,i}$ is the contribution of load types on the nodes of the system, $D_{j,h}$ is the hourly distribution of types of load and $LP_{i(max)}$ is the maximum load at the particular node, set to be 120% of the actual data.
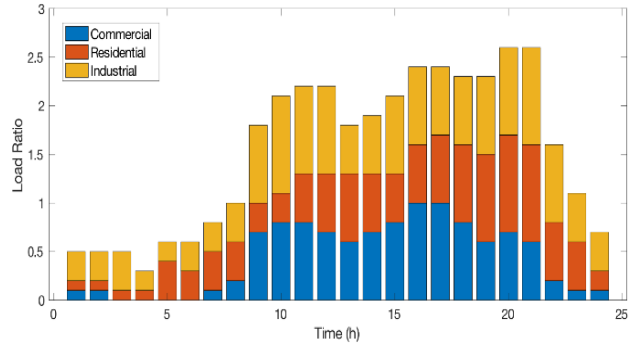

Fig. 5: Hourly Load Demand Chart

III. POWER FLOW USING FORWARD/BACKWARD SWEEP

In order to inspect the effect of SST model in the distribution system, power flow analysis using backward-forward sweep approach is applied [26].

A. Backward Sweep

In the backward sweep, voltage at each bus are set 1 p.u and current flowing in all the branches is calculated starting from last node and moving towards first node. Bus 1 is considered as slack bus.

$$I_i = \left(\frac{S_i}{V_i}\right)^* \qquad (10)$$

$$S_i = P_i + jQ_i \qquad (10.1)$$

$$I_i = \frac{P_i - jQ_i}{V_i} \tag{10.2}$$

where $i = 0,1 \dots, n$, V_i is the voltage at i_{th} bus, I_i is the branch current, S_i is the apparent power of the system, P_i and Q_i are the active and reactive power at i_{th} bus.

B. Forward Sweep

In the forward sweep the voltage at each bus are calculated by using the branch currents calculated using (10.2). Voltages are calculated starting from first node and moving towards last node.

$$V_{i+1} = V_i - I_{i,i+1} \times Z_{i,i+1} \tag{11}$$

$$Z_{i,i+1} = R_{i,i+1} + jX_{i,i+1} \tag{11.1}$$

here $Z_{i,i+1}$ is the branch impedance, $R_{i,i+1}$ and $X_{i,i+1}$ respectively are the resistance and the reactance of the specified line.

IV. PROBLEM FORMULATION

The goal of presented paper is to diminish distribution system active power losses and voltage deviations by optimizing the reactive power management in SSTs connected to the network. The objective function of the specified problem can be written as presented in (12).

$$O.F = min \left\{ \frac{PLoss_{before}}{PLoss_{after}} + \frac{\Delta V_1}{\Delta V_0} \right\} \tag{12}$$

where, $PLoss_{after}$ is the value of power loss after optimization and $PLoss_{before}$ is the power loss before optimization. Similarly, ΔV_0 and ΔV_1 represent the voltage deviation before and after optimization.

A. Constraints

The optimization problem has to fulfill certain equality and inequality constraints, the details of which are as follow:

i. SST Constraints:

The values of modulation coefficients are selected optimally between 0 and 1, whereas, the phase angles range from $-\frac{\pi}{4}$ to $\frac{\pi}{4}$ as shown below.

$$\begin{cases} 0 \le C_1, C_2 \le 1 \\ -\frac{\pi}{4} \le \delta_1, \delta_2 < \frac{\pi}{4} \end{cases} \tag{13}$$

Similarly, the active power on the either side of the SST must be same, also the magnitude of active and reactive power on both sides of SST must not exceed the rated apparent power of SST.

$$\begin{cases} P_1 = P_2 \\ \sqrt{P_1{}^2 + Q_1{}^2} \le S \\ \sqrt{P_2{}^2 + Q_2{}^2} \le S \end{cases} \tag{14}$$

where, P_1, P_2, Q_1, Q_2 are the real and reactive power on both sides of SST and S is the apparent power.

ii. Power Handling Constraint:

Generation should meet the system's demand including losses.

$$\begin{cases} P_{Gi} - P_{Di} + P_{loss,i} \\ Q_{Gi} - Q_{Di} + Q_{loss,i} \end{cases} \tag{15}$$

where, P_{Gi}, Q_{Gi} express the generated active and reactive power, P_{Di}, Q_{Di} are the real and reactive power demands and $P_{loss,i}, Q_{loss,i}$ are the active and reactive power loss at any i_{th} bus.

iii. Voltage Magnitude Constraint:

The voltage deviation constraint as given in (16) must not exceed the permissible voltage limits.

$$V_{i,min} \le V_i \le V_{i,max} \tag{16}$$

where, $V_{i,min}$ and $V_{i,max}$ are the allowable voltage limits on bus i.

iv. DG Power Constraints:

The active and reactive power of the DGs should not exceed their minimum and maximum limits.

$$\begin{cases} P_{Gi,min} \le P_{Gi} \le P_{Gi,max} \\ Q_{Gi,min} \le Q_{Gi} \le Q_{Gi,max} \end{cases} \tag{17}$$

where $P_{Gi,min}, Q_{Gi,min}, P_{Gi,max}, Q_{Gi,max}$ are the minimal and maximal amount of active and reactive power generation limits of RESs i.e., solar and wind.

B. Moth Swarm Algorithm

In this paper Moth swarm algorithm (MSA) is used to perform the optimization task, the performance of which is compared with moth flame optimization (MFO) technique. MSA has several benefits over MFO in different aspects i.e., convergence rate, robustness and better performance in fulfilling the objective function. In MFO, the swarm of moths is considered as a whole to search for the best solution, however, MSA categorizes the swarm in to groups in order to explore the search space individually which consequently enhances the abilities to swarm to explore and exploit the search area in more effective manner.

The moths in MSA are equipped with a temporary storage which enables them to store the optimum values achieved during the process of optimization. Moreover, each group of moths update their position separately using the associative process of learning which saves the required memory. Another promising feature of MSA is that it utilizes the searching capabilities of pathfinders, prospectors and onlookers to explore the search space entirely and effectively which eliminates the drawback of trapping the solution in local optima which is one of the major flaws of MFO.

MSA is the natured inspired metaheuristic algorithm. Moths follow the moon light at the night by using celestial navigation to find their food. They move in spiral path travelling straight

towards the brightest light source keeping a fixed angle with reference to the light source using transverse orientation mechanism. Brief working of the algorithm is depicted in the Fig. 6.
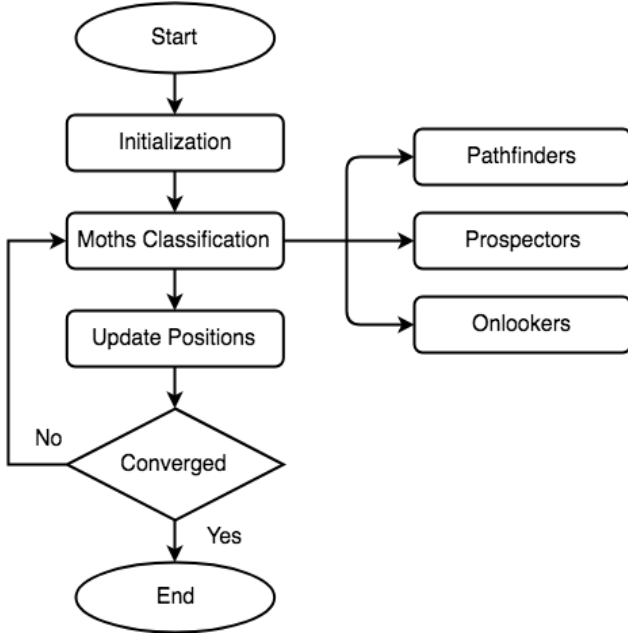

Fig. 6: Flow Chart oF MSA

i.   Initialization:

Initially for a given dimension of the problem and population, positions of moths are randomly initialized.

$$x_{ij} = rand[0,1] \times \left(x_j^{max} - x_j^{min}\right) + x_j^{min} \qquad (18)$$

Where, i is the population size and j represents the dimensions of the problem.

ii.   Classification of Moths:

Moths in a swarm are categorized in to three groups to enhance the efficiency and convergence of the algorithm.

- Pathfinders

After initialization of the algorithm the best performing group of moths are designated as pathfinders. They have the ability to discover the new areas in the search space. There might be a possibility that the best solution may exist other than the crowded area, for that reason pathfinders are forced to explore areas which are not densely crowded to improve the diversity of the algorithm.

- Prospectors

The group of moths that have next best position after pathfinders are designated as prospectors. They are supposed to look in the surrounding area marked by pathfinders. If at any time the prospector finds a better solution than the pathfinder, the prospector is promoted to become pathfinder. They follow a random spiral path around the marked light sources and their number decreases with time t after T iterations as:

$$n_f = round\left((n - n_p) \times \left(1 - \frac{t}{T}\right)\right) \qquad (19)$$

- Onlookers

This is the group of moths with the least ability to find the best solution. Their number increases as the number of prospectors decreases, consequently improving the convergence rate of algorithm. These moths travel directly towards the brightest light source. To enhance the ability of onlookers to search for the solution effectively, onlookers use Gaussian probabilistic distribution and associative learning procedure with Short-term memory.

At the end of each iteration groups of moths interact with each other and revise their position based on crossover operation. The best performing moths among the onlooker and prospectors are designated as pathfinders. The whole process continues until the convergence criteria are met. The complete attributes of the algorithm can be found [27].

V.   SIMULATION RESULTS

A.   Case study

The performance of the presented reactive power management technique is analyzed using IEEE 33-bus distribution system presented with exceptions of micro turbines and storage batteries, the modified distribution system is shown in the Fig. 7 [28].
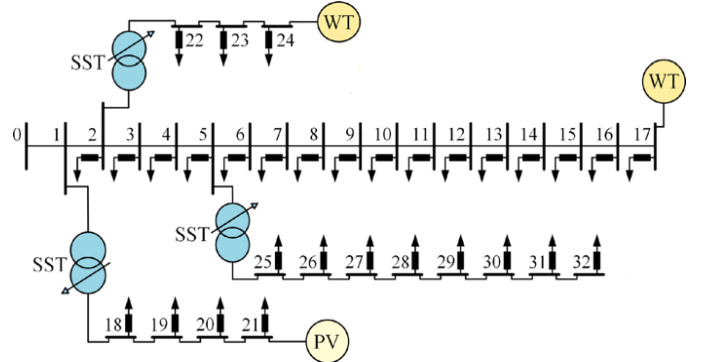

Fig. 7: Modified Ieee 33 Bus System

The load data of the standard test system is categorized into residential, commercial and industrial using (9). Three different case studies have been developed to analyze the performance of the SST model.

- The base case analyzes the performance of the system in the absence of RES and SST.
- Case 1 refers to the analysis of the system by incorporating both the RES and SST.
- In case 2 only the effect of SST on the system performance is considered.

Specifications of the system are enlisted in Table I.

Table I: System Parameters

S. No	IEEE 33-bus System		
	Parameters	*Value*	*Quantity*
1	Base MVA	100	-
2	Base KV	12.66	-
3	PV System	100 KW	1
4	Wind Turbine	100 KW	2
5	SST	1.6 MVA	3
6	V_{min}	0.95 P.u	-
7	V_{max}	1.05 P.u	-
8	x_1	0.24 ohm	-
9	x_2	0.12 ohm	-

Table II: Performance Comparison Case 1

Average Values	Case 1: Including RES and SST		
	MFO	*MSA*	*Improvement*
Time (s)	43.6	41.6	4.58 %
Objective Fucntion	0.97	0.93	4.12 %
Losses (KW)	113.9	92.0	19.2 %

Table III: Performance Comparison Case 2

Average Values	Case 2: Including SST only		
	MFO	*MSA*	*Improvement*
Time (s)	35.9	34.2	4.73 %
Objective Fucntion	1.01	0.95	5.94 %
Losses (KW)	128.5	104.8	18.4 %

Table IV: Average Values of SST Control Variables

| Control variables of SST		
Average Values	*MFO*	*MSA*
C_1	0.357187806	0.224435484
C_2	0.845180877	0.571591872
δ_1	0.024237982	0.023595243
δ_2	0.056514998	-0.022063153

The number of search agents (moths) is taken to be 30 and the number of pathfinders is 6, while maximum iterations are set to 100. The performance of the algorithm is compared with Moth Flame Optimization (MFO). Simulations are run for 30 times and the average values of simulation time, objective function and power loss are recorded. Additionally, the standard deviation of the minimum and maximum values of objective function achieved using MSA is obtained to be 0.007 in 30 runs of the simulation, which reflects the better convergence capabilities of the presented algorithm. The comparison of the two techniques is presented in the Table II and Table III. Whereas, Table 4 shows the average optimum values of control parameters of SST. Simulations are run 30 times for both of the optimization algorithms and the average values of modulation coefficients and phase angles of SST are computed accordingly. Consequently, the reactive power

flowing in the respective branches is controlled based on the values of SST control variables.

B. Results and Discussion

To validate the performance of the presented work numerous case studies have been developed considering multiple scenarios. The findings of research are critically analyzed and are presented in the form of comparative tables and graphs. The simulations are performed on core i7 2GHz MacBook pro with 8GB RAM and 2018a version of MATLAB is used. The results in Table II show the comparison of the performance of both the algorithms under case 1, which considers the impact of using the combination of RES and SST. In case 1, the presented technique (MSA) shows 4.58% betterment with regard to simulation time, also the value of objective function obtained has an improvement of 4.12% in contrast with the other technique (MFO). Similarly, there is a prominent refinement of 19.2% in percentage power loss of the system obtained through MSA. Similarly, Table III shows the comparative performance results considering case 2, in which the impact of SST only is analyzed. The simulation time of MSA has an improvement of 4.73%, also as compared to case 1, case 2 has betterment in simulation time because the system only considers SST so simulation time is saved. Likewise, the value of objective function obtained through MSA has an improvement of 5.94% as compared to MFO. The system power losses attained in case 2 by MSA is 18.4% better in contrast with MFO, but as compared to case 1, there is a decrement in the power loss improvement which shows the importance of RES in enhancing the system performance. There is noticeable improvement in power loss under both the cases 1&2 in contrast with the base case having power loss of 302 KW. The voltage profile of the system indicates that voltage remained well under the permissible range.

Fig. 8 shows the impact of reactive power compensation achieved through the combination of RES and SST using MSA and MFO algorithms. It can be seen that there is an improvement in the voltage at different system nodes. An evident reduction of voltage sag can be seen in Fig. 8(a) in contrast with the one obtained through MFO, Fig. 8(b).
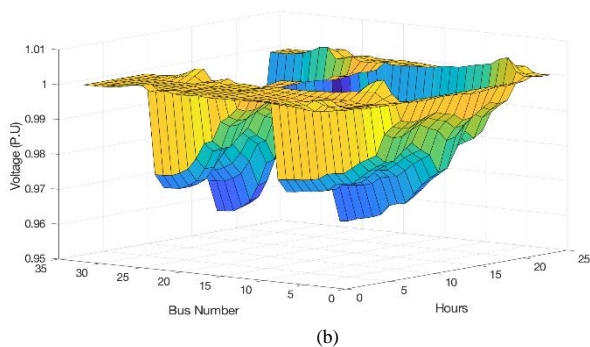

(a)
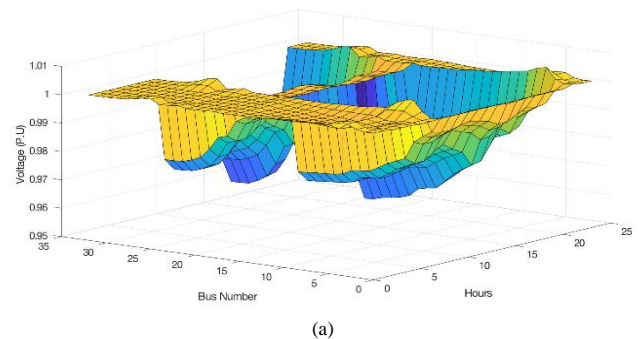
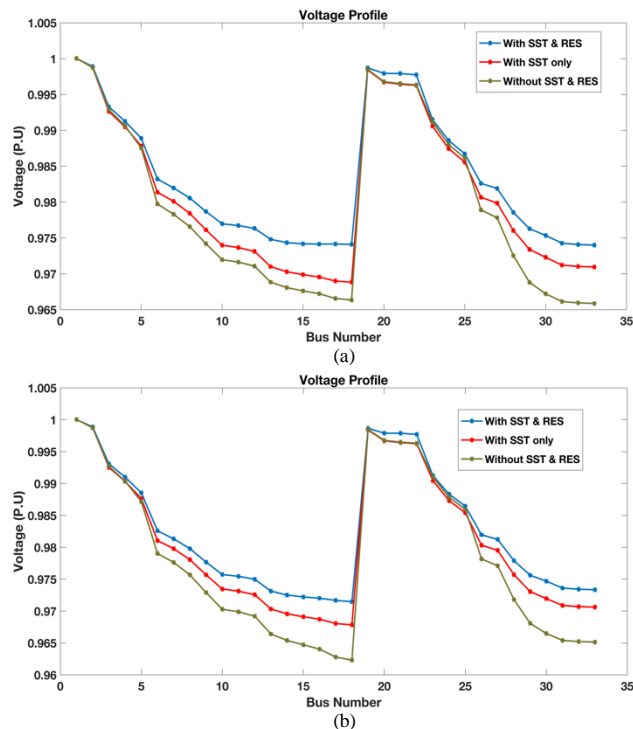Fig. 8: Voltage Profile using (a) MSA and (b) MFO for Case 1

(a)

(b)

Fig. 9: Comparison of System Voltage at 22ND Hour using (a) MSA and (b) MFO

Similarly, voltage of the system under three cases have been compared under maximum loading conditions at 22$_{nd}$ hour. The comparison is carried out separately for the different optimization techniques as shown in the Fig. 9. The results show the better performance of MSA over MFO, the voltage at different nodes can be seen to betterment in comparison with the different scenarios. The system performance is analyzed by first considering the impact of combined operation of RES and SST, then the impact of SST only and lastly the performance is checked without using RES and SST. The best results are obtained using the combination of RES and SST using MSA especially at node 18 where the voltage profile is lifted well above from 0.962 V$_{p.u}$ to approximately 0.975 V$_{p.u}$, in the same manner the power loss is significantly reduced.

VI. CONCLUSION

In this work, the reactive power handling capabilities of an SST are analyzed. Load flow solution is applied to the system under test, in order to check the impact of SST on voltage profile. Additionally, an optimization technique based of Moth Swarm Algorithm (MSA) has been applied and compared with the other algorithms. The algorithm further refines the performance of the system by significantly reducing the system power losses. Moreover, the system performance was analyzed by considering the combined effect of RES and SST and by taking SST only. The proposed algorithm appears to have better convergence characteristics and better accuracy in contrast with the other algorithms. The proposed research can help to enhance the system integration and flexibility to handle the AC/DC component at different integration levels. Also, the reactive power handling can be attained in a more effective way if the reactive power handling capabilities of PV system and SST are used collectively.

REFERENCES

[1] Lopes, J. A. P., Hatziargyriou, N., Mutale, J., Djapic, P., & Jenkins, N. (2007). Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities. Electric Power Systems Research, 77(9), 1189–1203.

[2] Ding, T., Liu, S., Wu, Z., & Bie, Z. (2017). Sensitivity-based relaxation and decomposition method to dynamic reactive power optimisation considering DGs in active distribution networks. IET Generation, Transmission and Distribution, 11(1), 37–48.

[3] Paaso, E. A., Liao, Y., & Cramer, A. M. (2014). Formulation and solution of distribution system voltage and VAR control with distributed generation as a mixed integer non-linear programming problem. Electric Power Systems Research, 108, 164–169.

[4] Hong, Y. Y., & Yang, Y. L. (1999). Expert system for enhancing voltage security/stability in power systems. IEE Proceedings: Generation, Transmission and Distribution, 146(4), 349–354.

[5] Baerthlein, E. M., & Panosyan, A. (2016). U.S. Patent No. 9,400,512. Washington, DC: U.S. Patent and Trademark Office.

[6] Askarzadeh, A. (2016). Capacitor placement in distribution systems for power loss reduction and voltage improvement: A new methodology. IET Generation, Transmission and Distribution, 10(14), 3631–3638.

[7] Etemadi, A. H., & Fotuhi-Firuzabad, M. (2008). Distribution system reliability enhancement using optimal capacitor placement. IET Generation, Transmission & Distribution, 2(5), 621-631.

[8] Gomez-Exposito, A., Conejo, A. J., & Canizares, C. (2018). Electric energy systems: analysis and operation. CRC press.

[9] Abu-Siada, A., Budiri, J., & Abdou, A. F. (2018). Solid state transformers topologies, controllers, and applications: State-of-the-art literature review. Electronics MDPI, 7(11), 1–18.

[10] She, X., Huang, A. Q., & Burgos, R. (2013). Review of solid-state transformer technologies and their application in power distribution systems. IEEE Journal of Emerging and Selected Topics in Power Electronics, 1(3), 186–198.

[11] Ortiz, G., Leibl, M. G., Huber, J. E., & Kolar, J. W. (2016). Design and experimental testing of a resonant DC-DC converter for solid-state transformers. IEEE Transactions on Power Electronics, 32(10), 7534–7542.

[12] Ushkewar, S., Dake, V., & Shinde, V. (2017). Designing of solid state pulse power modulator by fabrication of pulse transformer. 2017 Innovations in Power and Advanced Computing Technologies, i-PACT 2017, 1–5.

[13] Huber, J. E., & Kolar, J. W. (2016, September). Solid-State Transformers: On the Origins and Evolution of Key Concepts. IEEE Industrial Electronics Magazine, 10(3), 19–28.

[14] Freedman, D. H. (2011). Ten Breakthrough Technologies. MIT Technology Review.

[15] Krishnamoorthy, H. S., Enjeti, P. N., & Sandoval, J. J. (2017). Solid-state transformer for grid interface of high-power multipulse rectifiers. IEEE Transactions on Industry Applications, 54(5), 5504–5511.

[16] Al-Hafri, A., Ali, H., Ghias, A., & Nasir, Q. (2016). Transformer-less based solid state transformer for intelligent power management. International Conference on Electronic Devices, Systems, and Applications, 1, 1–4.

[17] Hunziker, C., & Schulz, N. (2017). Potential of solid-state transformers for grid optimization in existing low-voltage grid environments. Electric Power Systems Research, 146, 124–131.

[18] Syed, I., Khadkikar, V., & Zeineldin, H. H. (2018). Loss reduction in radial distribution networks using a solid-state transformer. IEEE Transactions on Industry Applications, 54(5), 5474–5482.

[19] Grudinin, N. (1998). Reactive power optimization using successive quadratic programming method. IEEE Transactions on Power Systems, 13(4), 1219–1225.

[20] Hughes, A., Sun, D. I., Ashley, B., Brewer, B., Wa, B., Way, N., & Tinney, W. F. (1984). Optimal power flow by newton approach. IEEE Transaction on Power Apparatus and Systems, PAS-103(10), 2864–2880.

[21] Granville, S. (1994). Optimal reactive power dispatch through interior point methods. IEEE Transactions on Power Systems, 9(1), 136–146.

[22] Dubey, H. M., Pandit, M., & Panigrahi, B. K. (2018). An overview and comparative analysis of recent bio-inspired optimization techniques for wind integrated multi-objective power dispatch. Swarm and Evolutionary Computation, 38, 12–34.

[23] Ng Shin Mei, R., Sulaiman, M. H., Mustaffa, Z., & Daniyal, H. (2017). Optimal reactive power dispatch solution by loss minimization using moth-flame optimization technique. Applied Soft Computing Journal, 59, 210–222.

[24] Kayal, P., & Chanda, C. K. (2015). Optimal mix of solar and wind distributed generations considering performance improvement of electrical distribution network. Renewable Energy, 75, 173–186.

[25] Milani, A. E., & Haghifam, M. R. (2013). An evolutionary approach for optimal time interval determination in distribution network reconfiguration under variable load. Mathematical and Computer Modelling, 57(1-2), 68–77.

[26] Ghosh, S., & Das, D. (1999). Method for load-flow solution of radial distribution networks. IEE Proceedings: Generation, Transmission and Distribution, 146(6), 641–646.

[27] Mohamed, A. A. A., Mohamed, Y. S., El-Gaafary, A. A. M., & Hemeida, A. M. (2017). Optimal power flow using moth swarm algorithm. Electric Power Systems Research, 142, 190–206.

[28] Shi, J., Yang, W., Xue, F., Qiao, W., & Zhang, D. (2019). Reactive power optimization of an active distribution network including a solid state transformer using a moth swarm algorithm. Journal of Renewable and Sustainable Energy, 11(3).