Proceedings of 15th IOE Graduate Conference
Peer Reviewed
Year: 2024 Month: May Volume: 15
ISSN: 2350-8914 (Online), 2350-8906 (Print)

Optimal Siting and Sizing Of SSSC in INPS using Modified Salp Swarm Algorithm Considering Optimal Reactive Power Dispatch Problem

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Abstract

Effective coordination between power generation and demand is vital for maximizing efficiency, especially with the increasing demand for electrical energy. Flexible AC Transmission System (FACTS) devices, like the Static Synchronous Series Compensator (SSSC), enhance transmission efficiency by improving power transfer capacity and stability. Integrating SSSC presents challenges due to nonlinear functions, complicating the Optimal Reactive Power Dispatch (ORPD) problem. To address this, a Modified Salp Swarm Algorithm efficiently determines the optimal location and rating of SSSC, comparing results with the IEEE 30-bus system. Our approach aims to minimize power losses, voltage deviations, and improve the voltage profile, demonstrating its effectiveness in optimizing power system operation with SSSC controllers. After solving the ORPD problem and load flow analysis, initial line losses of 119.108 MW (5.8% of total load) reduced to 35.336 MW (1.72% of total load) after including SSSC in INPS. The optimal SSSC size is 58.307 MVA, located on line Lahan to Kusaha, resulting in significant power loss reduction and voltage profile improvement.

Keywords

Flexible alternating current transmission systems, static synchronous series compensator, Optimal reactive power dispatch, Integrated Nepalese Power System

1. Introduction

In the sector of electrical power systems, managing transmission networks efficiently has become increasingly crucial with rising energy demands. Flexible Alternating Current Transmission Systems (FACTs) devices [1]are indispensable tools for enhancing grid controllability, stability, and efficiency [2]. Among these devices, the Static Synchronous Series Compensator (SSSC) is notable for optimizing reactive power dispatch within power systems. By inserting controllable voltage in series with transmission lines, the SSSC regulates active and reactive power flow, ensuring voltage stability and enhancing transmission capacity [3]. SSSC is modelled within the load flow problem by representing it as power injections at the nodes [4] [5] of the line where it is installed. These power injections, which represent the SSSC, are used as inputs in a power flow calculation. [6]

The optimal management of reactive power resources, known as Optimal Reactive Power Dispatch (ORPD)[4], is essential for maintaining system integrity and efficiency. This involves determining settings for reactive power sources to uphold voltage levels within limits while minimizing power losses [5, 6]. However, as power systems evolve, the ORPD problem becomes more complex[7], requiring innovative optimization techniques [8].

This paper is using an optimization algorithm [9] based on the Modified Salp Swarm Algorithm (MSSA) [10] to address the ORPD problem[11] and determine optimal SSSC locations and ratings. MSSA adjusts control variables iteratively to optimize the specified objective function for power system operation on the Integrated Nepal Power System (INPS) and comparison with the IEEE 30-bus system [12] demonstrate the algorithm's efficacy in minimizing losses, voltage deviations, and enhancing stability. Integration of SSSC within the optimization framework promises significant improvements in system performance, offering a cost-effective solution for power system optimization.

2. Approach

The main objective of this paper is to find the optimal size and the location of the SSSC in the INPS using Modified Salp Swarm Algorithm. To optimize the power losses and voltage deviation reduction SSSC model is developed with Optimal Reactive Power Dispatch solution. Load flow analysis is carried out in INPS without SSSC and with SSSC and result is compared with the IEEE 30-Bus system.

2.1 SSSC Modeling and Formulation

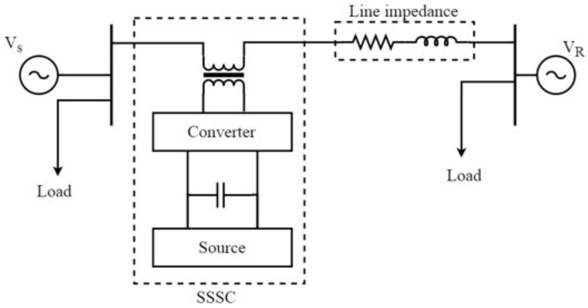

Figure 1: Schematic diagram of SSSC

The SSSC is modeled in load flow analysis as power injections at the nodes of the transmission line where it is installed, rather than directly incorporating it into calculations. Initially, load flow analysis is performed without considering the SSSC, yielding a mismatch vector indicating deviation from desired conditions. The power injections representing the SSSC are adjusted iteratively to minimize this mismatch vector. Convergence is reached when the mismatch vector becomes sufficiently small, indicating steady-state conditions satisfying SSSC requirements. The SSSC can be modeled as a voltage source in series with impedance.

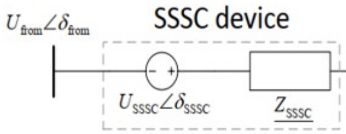

Figure 2: The SSSC Device Normally Modelled

This directly simplifies into:

$$Z_{\text{Total}} = Z_{\text{SSSC}} + Z_{Line} \tag{1}$$

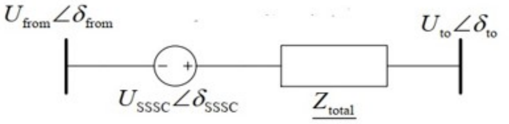

Figure 3: SSSC equivalent branch, summing impedences

The Norton equivalent of figure 3 we obtained is shown in figure 4:

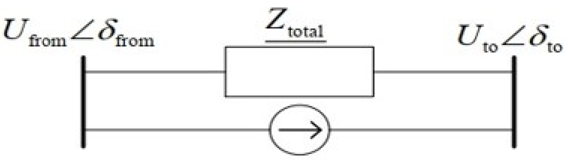

Figure 4: SSSC equivalent branch, Norton equivalent

$$I_G = \frac{U_{\text{SSSC}} < \delta_{\text{SSSC}}}{Z_{\text{Total}}} \tag{2}$$

The latter can be restated in terms of power injections in the following ways:

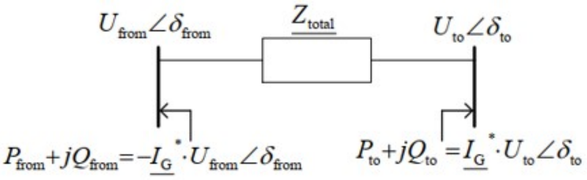

Figure 5: SSSC equivalent nodal power injections at ends of line of insertion

$$P_{\text{from}} + jQ_{\text{from}} = -I_G * U_{\text{from}} < \delta_{\text{from}} \tag{3}$$

$$P_{\text{to}} + jQ_{\text{to}} = I_G * U_{\text{to}} < \delta_{\text{to}} \tag{4}$$

The power injections will model an SSSC device. The parameters of the SSSC device, $U_{\text{SSSC}}$and δ_{SSSC} , can then be calculated from the injected powers and the voltages and angles at the bus of SSSC device as:

$$U_{\text{SSSC}} < \delta_{\text{SSSC}} = Z_{\text{Total}}.I_G \tag{5}$$

2.2 Optimal Reactive Power Dispatch (ORPD) Problem Formulation for Different Objective Functions

The aim of the ORPD problem is to find the values of control variables that minimize the objective function while satisfying certain equality and inequality conditions. The control variables include various parameters that can be adjusted, such as generator powers and bus voltages. The dependent variables are the outcomes or results of the optimization, representing aspects like power generation, bus voltages, and the impact of the SSSC. The formulation of these eqations are from the reference [8].

The ORPD problem minimizes an objective function while adhering to equality and inequality constraints. The objective is to optimize system performance by adjusting control variables while ensuring operational constraints are met. The independent variables include factors such as generated power, voltages, and reactive powers, while dependent variables encompass various system parameters like generated power at the slack bus and power flow in transmission lines. Constraints are categorized as equality and inequality, ensuring specific conditions are met precisely and imposing limits on variables, respectively. Ultimately, ORPD aims to enhance the efficiency and stability of power systems.

2.2.1 Minimization of Power Losses and Voltage Deviations

The minimization of active power losses and voltage deviations in single objective function can be formulated as:

$$F = \alpha \sum_{i=1}^{NL} P_{\text{losses}} + \beta \sum_{i=1}^{NL} [V_i - V_{\text{ref}}] \tag{6}$$

Here, F represents the objective function, where α and $\beta$are weighting factors representing the relative importance of minimizing power losses and voltage deviations, respectively. NL denotes the number of transmission lines, P_losses represents active power losses, V_i represents the voltage magnitude at bus i, and V_ref is the reference voltage, commonly set to 1. This objective function integrates the goals of reducing both power losses and voltage deviations, allowing for a unified optimization approach that balances both objectives according to the specified weighting factors.

2.2.2 Constraints

Equality Constraints

These constraints represent the balanced load flow equations as:

$$P_{Gi} - P_{Di} = \sum_{j=1}^{NB} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_{ij}) \tag{7}$$

$$Q_{Gi} - Q_{Di} = \sum_{j=1}^{NB} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_{ij}) \tag{8}$$

Inequality Constraints

These constraints which represent the operating limits of system component include:

$$P_{Gi}^{min} \leq PGi \leq P_{Gi}^{max} i = 1,2,....,NG \tag{9}$$

$$V_{Gi}^{min} \leq VGi \leq V_{Gi}^{max} i = 1,2,....,NG \tag{10}$$

$$Q_{Gi}^{min} \leq QGi \leq Q_{Gi}^{max} i = 1,2,....,NG \tag{11}$$

$$V_{Li}^{min} \leq VLi \leq V_{Li}^{max} i = 1,2,....,NPQ \tag{12}$$

$$V_{se}^{max} \leq Vse \leq V_{se}^{min} \tag{13}$$

$$\theta_{se}^{max} \leq \theta se \leq \theta_{se}^{min} \tag{14}$$

The system constraints which added to the objective function are taken into consideration by using the penalty factors related the constraints. Thereby, the objective function can be formulated as:

$$\begin{aligned} F_g(x,u) = & Fi(x,u) + eG(PG1 - P_{G1}^{lim})2+ \\ & eQ\sum_{i=1}^{NPV}(Q_{Gi} - Q_{Gi}^{lim}2 + ev\sum_{i=1}^{NPQ}(V_{Li} - V_{Li}^{lim})2+ \\ & es\sum_{i=1}^{NTL}(S_{Li} - S_{Li}^{lim})2 + eF(V_{se} - V_{se}^{lim})2+ \\ & et(\theta_{se} - \theta_{se}^{lim})2 \end{aligned} \tag{15}$$

2.3 The Modified Salp Swarm Algorithm (MSSA)

Mathematical Model of MSSA

In the Salp Swarm Algorithm (SSA), inspired by the behavior of salps in deep oceans, the population is divided into two groups: leaders and followers. The leader, positioned at the front of the chain, guides the swarm, while the rest of the salps act as followers, following either the leader directly or indirectly. This swarming behavior, resembling the formation of salp chains, aids in efficient movement and potentially in locating food sources.

In SSA, the position of salps is represented in an n-dimensional search space, where n corresponds to the number of variables in a given problem. This position information is stored in a two-dimensional matrix known as Zn, facilitating the exploration of the search space by the salps.

To update the position of the leader the following equation is proposed:

$$Z_n^i = \begin{cases} Z_{LD} + C_1(u_n - l_n)c_2 + l_n & c_3 < 0 \\ Z_{LD} + C_1(u_n - l_n)c_2 + l_n & c_3 \geq 0 \end{cases} \tag{16}$$

where, Z_n^i and Z_{LD} represent the leader position and food source position, respectively. $U_n$and l_n are the upper and lower limits in nth dimension of search space.

$$C_1 = 2e^{-}\left(-\frac{4a}{A}\right) \tag{17}$$

In order to change the position of followers, the following expression is used.

$$Z_n^m = \frac{1}{2}ce^2 + v_0 e \tag{18}$$

Where, $m \geq 2$, $c = \frac{v_{final}}{v_o}$and $v = \frac{z - z_0}{e}$. The simulation time is depending on the iterations and the conflict between iteration is equal to 1 while considering $v_o = 0$, the Equation (16) will be as followed.

$$Z_n^m = \frac{1}{2}\left(Z_n^m + Z_n^{m-1}\right) \tag{19}$$

The MSSA is proposed to overcome the shortages of the conventional SSA which include its tendency to local optima. and stagnation for some cases. Two search strategies are presented for enhancing capability of the conventional SSA. The modification in SSA is utilized for boosting the exploration process by updating the locations of salps using the Levy flight distribution (LFD) to aid population to find new areas to overcome its stagnation. While the second modification depends upon modifying and updating the locations of salps in the spiral path around the best solution to enhance its exploitation. The first modification which based on the LFD is expressed as follows.

$$Z_{n-new}^m = Z_n^m + \propto +\text{Levy}(\beta) \tag{20}$$

Where $\propto$ refers to a step size parameter which is assigned as follows.

$$\propto +\text{Levy}(\beta) \sim 0.01\frac{u}{|v|^{\frac{1}{\beta}}}(Z_n^m - Z_{LD}) \tag{21}$$

where u and v are determined using (26) and (27) as follows:

$$u \sim N(0,\phi_u^2, v \sim N(0,\phi_v^2) \tag{22}$$

$$\phi_u = \left[\frac{\Gamma(1+\beta)x\sin(\Pi x\frac{\beta}{2})}{\Gamma\left[\frac{1+\beta}{2}\right]x\beta}\right]^{\frac{1}{\beta}}, \phi_v = 1 \tag{23}$$

where Γ represents the standard gamma function. The second modification is based on modifying the locations of salps in the spiral path around the best solution which can be expressed as follows:

$$Z_{n-new}^m = |Z_L D - Z_n^m| e^b t\cos(2\pi t) + Z_n^m \tag{24}$$

where b denotes a constant to describe the logarithmic spiral shape. To balance the exploration and the exploitation process an adaptive operator k is utilized to achieve this task.

$$K(t) = k_{\min} + \left(\frac{k_{\max} - k_{\min}}{T_{\max}}\right) \times t \tag{25}$$

where, $k_{\max}$ and $k_{\min}$ are the maximum and the minimum k limits. Finally, it is worth mentioned that searching capability of the MSSA is improved by enhancing the exploration phase using the LFD by applying Eq. (18) at the first iteration when the value of k is small while the exploitation phase is enhanced using the variable bandwidth transition by applying Eq. (22) at the final iteration when the value of k is large.

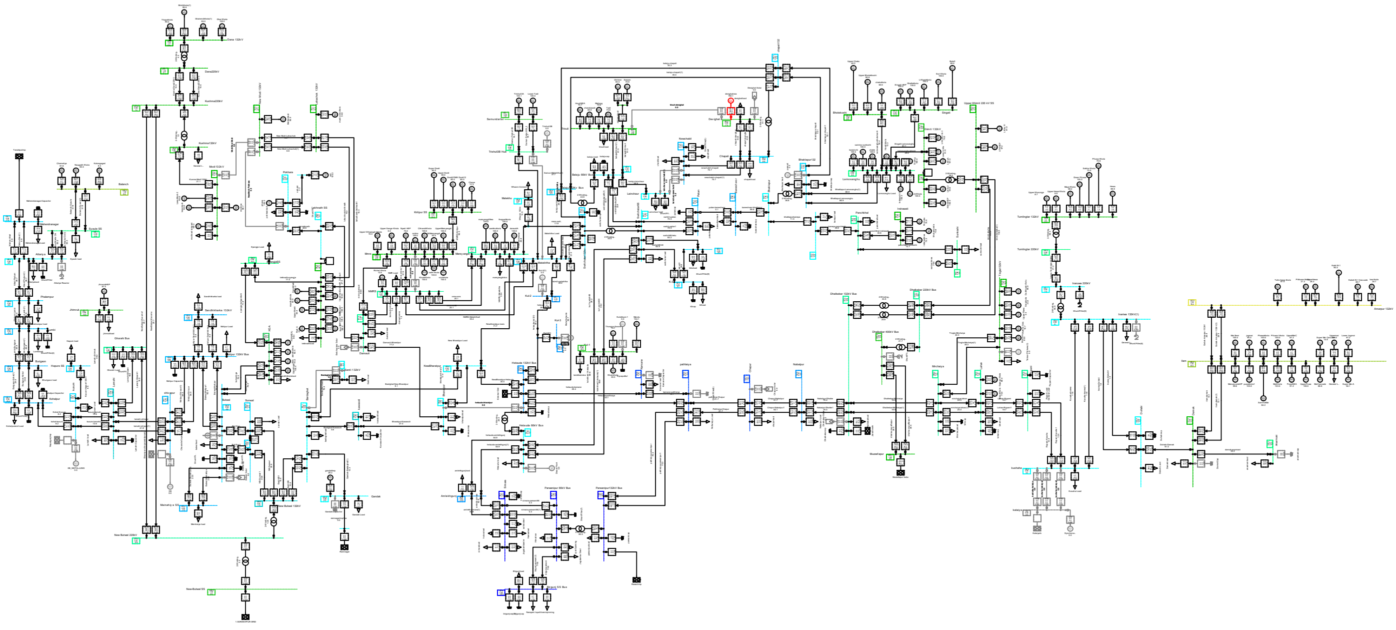

Figure 6: Integrated Nepalese Power System

2.4 Single Line Diagram of Integrated Nepalese Power System

The Integrated Nepal Power System (INPS) is the primary electrical grid network that connects power generation facilities, transmission lines, substations, and distribution networks across Nepal into a unified system. It serves as the backbone of the country's electricity infrastructure, facilitating the transmission and distribution of power from various sources to consumers throughout Nepal. INPS has 400 kV, 220 kV, 132 kV, 66 kV, 33 kV and 11 kV transmission network in which 132 kV network has mostly used in transmission network in all over Nepal. In INPS Dhalkebar and Muzzaffarpur are the maximum capacity substation which has 400 kV double circuit line having highest transmission capacity. The total installed capacity in INPS is 3320 MW but the peak load is 2010 MW. In dry season generation does not meet the demand so power is imported from Indian grid through Dhalkebar and Muzzaffarpur line but in wet season power is surplus so it is exported to India. Nepal has Marsyandi, Middle Marsyangdi, Kaligandaki and Chameliya as highest capacity PROR. Kulekhani-I, Kulekhani-II and Kulekhani-III and only storage type of plant in all over Nepal. Mostly generation are in hilly region and load are mostly in terai region due to which there congestion in transmitting the line and disturbance in voltage in the line.

2.5 Flow Chart of MSSA to solve ORPD problem with Optimal inclusion of SSSC

Hence, the Modified Salp Swarm Algorithm (MSSA) outlined in the flowchart presents a novel approach to optimizing power systems, leveraging the collective behavior of salp populations. By iteratively updating the positions of salps based on fitness evaluations and incorporating randomness to maintain diversity, the algorithm aims to find optimal solutions for power system operation.

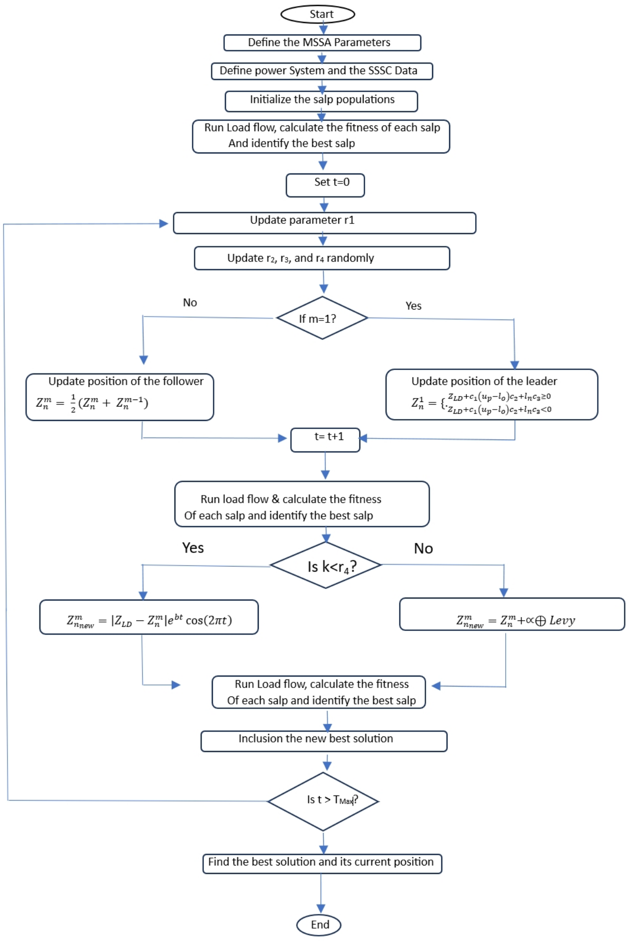

Figure 7: Flowchart of MSSA to solve ORPD problem with optimal inclusion of SSSC.

3. Results

In order to achieve the objective, coding was done in MATLAB programming for the INPS. ORPD problem was solved and load flow analysis was done using MSSA algorithm. Coding for Optimal placement of SSSC was done with the optimal calculation of optimal size and placement of SSSC. The line losses were calculated and was found to be 35.336 MW after the inclusion of SSSC in INPS which is very then the loss without SSSC in INPS which was 119.108 MW. The optimal size of SSSC was 58.307 MVA with the optimal location in line Lahan to Kusaha. The line from the Bus Lahan to the Bus Kusaha is most overloaded line in INPS.

These are the figures of convergence performance of MSSA for power losses and voltage profile with base case and optimized case in INPS with and without inclusion of SSSC in the system.

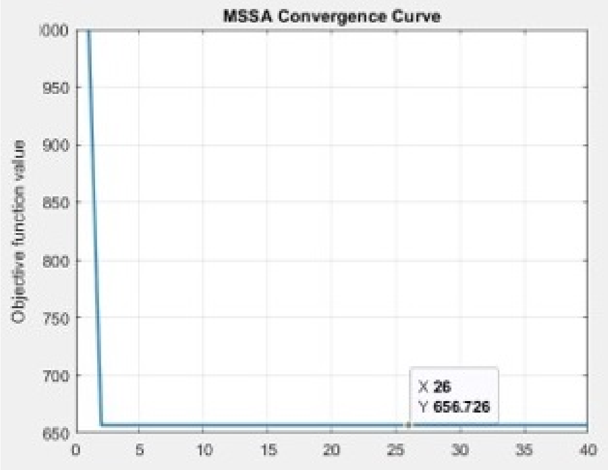

Figure 8: Convergence Performance of MSSA for Power Losses Minimization without inclusion of the SSSC on INPS

Here, figure 8 explains to the performance of the MSSA in minimizing power losses within the INPS, specifically without considering the inclusion of SSSC.

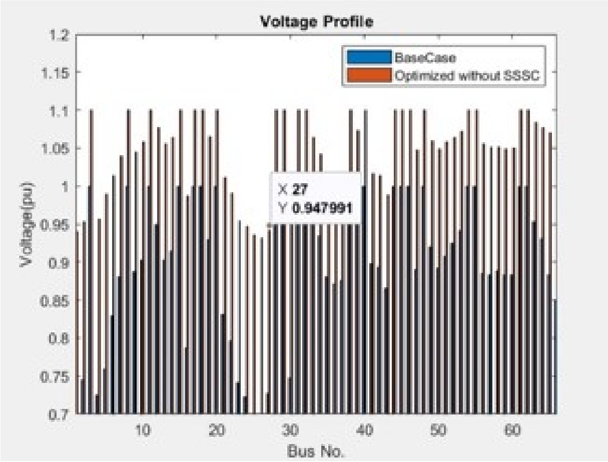

Figure 9: Voltage Profile without inclusion of the SSSC on INPS

Here, figure 9 explains the improvement of voltage profile in optimized case then the base case after performing load flow analysis without considering the inclusion of SSSC on INPS.

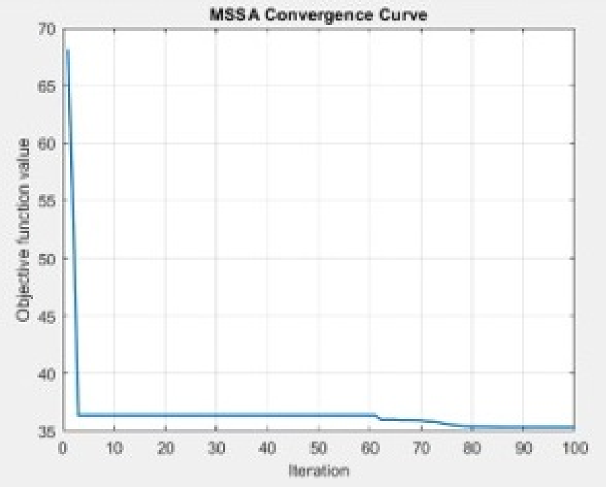

Figure 10: Convergence Performance of MSSA for Power Losses Minimization with inclusion of the SSSC on INPS

Here, figure 10 explains to the performance of the MSSA in minimizing power losses within the INPS, specifically with considering the inclusion of SSSC.

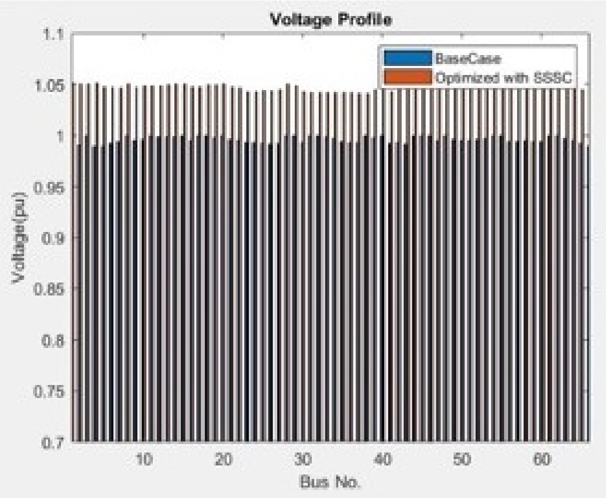

Figure 11: Voltage Profile with inclusion of the SSSC on INPS

Here, figure 11 explains the improvement of voltage profile in optimized case then the base case after performing load flow analysis on INPS with considering the inclusion of SSSC.

After comparing the figure 11 with figure 9, we see that voltage profile has been improved much after inclusion of SSSC in the system then the system without SSSC. Hence, line losses have been decreased.

Since for the actual scenario of Nepal, there are most ROR and PROR plant and the data has been taken for the wet condition. So, we cannot optimize the power and cannot fix its value in such as we can cannot stop the power plant to decrease the losses, the supply cannot be stopped and power should be exported. Power plant must run in full condition. For that case the value of voltage was not above 0.95 p.u. after optimization and there was no feasible solution within those constraints. Therefore, constraints were relaxed and taken to 0.9 p.u. and was able to get the solution.

Also, the result was compared with and without SSSC in IEEE 30-Bus system and found that there was decrease in the line losses which was 2.743 p.u. with SSSC and 2.984 p.u. without

SSSC. After optimization we get the optimum placement of SSSC in the Line 18 which is the branch 12-15 with the optimal size of SSSC as 72.39 MVA

Now the convergence performance of MSSA for power loss minimization without and with inclusion of SSSC and its voltage profile can be shown and compared as follows:

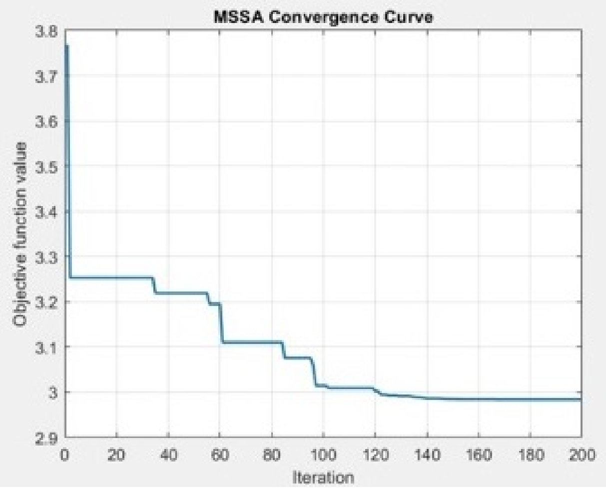

Figure 12: Convergence Performance of MSSA for Power Losses Minimization without inclusion of the SSSC on IEEE 30-Bus System

Here, figure 12 explains to the performance of the MSSA in minimizing power losses within the IEEE 30-Bus system, specifically without considering the inclusion of SSSC.

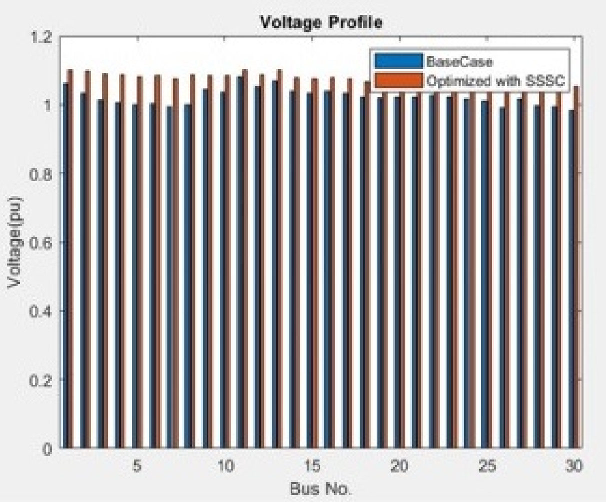

Figure 13: Voltage Profile without inclusion of the SSSC on IEEE 30-Bus System

Here, figure 13 explains the improvement of voltage profile in optimized case then the base case after performing load flow analysis without considering the inclusion of SSSC on IEEE 30-Bus system.

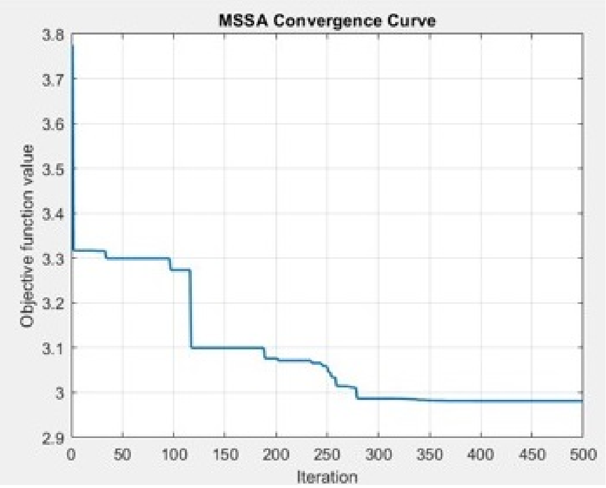

Figure 14: Convergence Performance of MSSA for Power Losses Minimization with inclusion of the SSSC on IEEE 30-Bus System

Here, figure 14 explains to the performance of the MSSA in minimizing power losses within the IEEE 30-Bus system, specifically with considering the inclusion of SSSC.

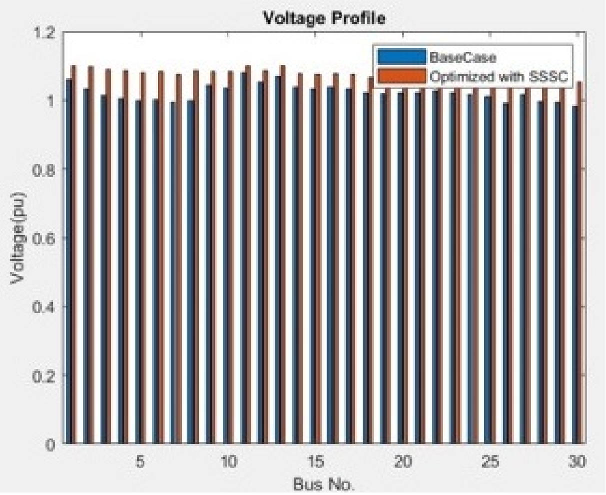

Figure 15: Voltage Profile with inclusion of the SSSC on IEEE 30-Bus System

Here, figure 15 explains the improvement of voltage profile in optimized case then the base case after performing load flow analysis on IEEE 30-Bus system with considering the inclusion of SSSC. After comparing the figure 15 with figure 13, we see that voltage profile has been improved much after inclusion of SSSC in the system then the system without SSSC. Hence, we became able to verify the result of INPS with the test result of IEEE 30-Bus system.

4. Conclusion

The objective of research is the optimal placement and size of SSSC and reduction of power losses after the placement. We see in INPS, there is reduction of power losses and improvement in voltage profile after optimization and inclusion of SSSC in the system. The similar work was done in IEEE 30-Bus system and got the similar result.

Acknowledgments

The authors are grateful to the assistance provided by personnel of Load Dispatch Centre from Nepal Electricity Authority in terms of data throughout this research.

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